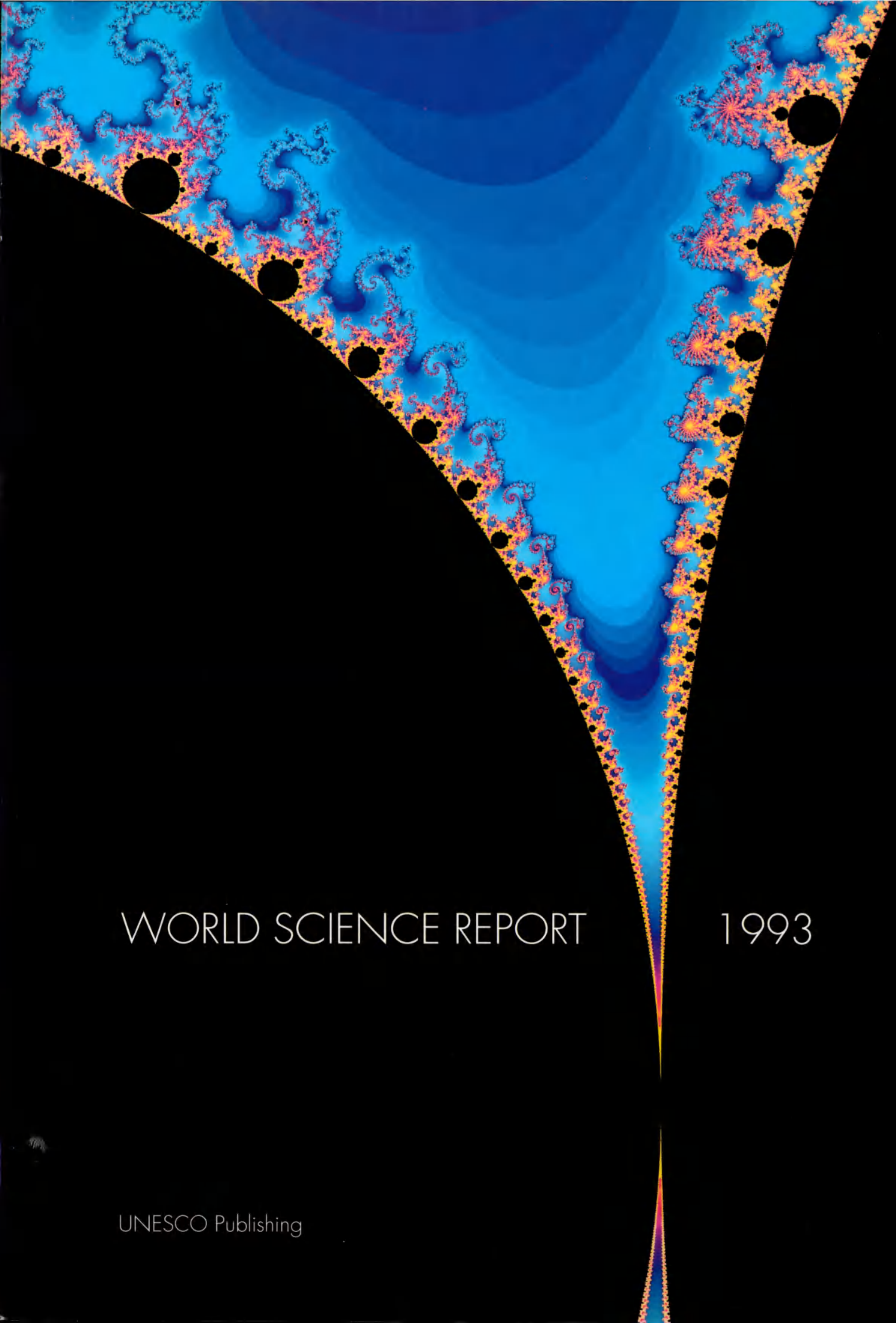

WORLD SCIENCE REPORT 1993

UNESCO Publishing

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PREFACE

Federico Mayor

Science and technology have played a key role in economic and social development in the century now drawing to a close. They have increasingly shown themselves, in the context of an accelerating growth of basic research and an ever more rapid application of its results, powerful instruments for the promotion of one of the main goals of the UN Charter – 'social progress and better standards of life in larger freedom'.

Yet the distribution of scientific and technological capacity, and of its fruits, remains very uneven from region to region and from country to country. Over four-fifths of research and development activities are concentrated in just a few industrialized countries. In 1990 expenditure on R&D as a percentage of gross national product was 2.9% for the industrialized world as a whole, whilst many developing countries could barely manage one-tenth of this level. Such figures provide substantial justification for the 'S' in UNESCO's title: one of its tasks is quite simply to help redress this imbalance.

Development cooperation is however only one aspect of UNESCO's larger function of intellectual cooperation – which is aimed at advancing and spreading knowledge worldwide, particularly in fields where an international approach is proving increasingly indispensable, and at fostering in the process ethical solidarity as a vital adjunct to intellectual exchanges. When, in this context, plans were mounted for the regular publication of a series of global reports on the areas within its competence, UNESCO – the only organization within the United Nations system responsible for cooperation in the sciences *per se* – naturally decided to devote one such report to science and technology in today's world. The UNESCO General Conference, at its twenty-sixth session in November 1991, subsequently authorized the preparation and publication of this first *World Science Report*.

The *Report* was planned with the help of an advisory group made up of individuals with a career-long interest in the organization and conduct of science. It is the product of many hands. Senior scientists and practised science watchers were invited to give us the benefit of their knowledge and experience in matters scientific by contributing individual chapters to the text.

The first part of the book attempts to give a global status report on science in the world today. Chapters within it are either devoted to complete regions or to countries or groups of countries whose science for one reason or another is at a particularly interesting stage of development. Authors were invited to give a personal appreciation of science in their parts of the world. Some chose to write accounts containing much data on research funding and manpower levels, reflecting the fact that some regions have a wealth of statistical material available on scientific research, training and development; other authors preferred to give more conceptual appraisals.

Part 2 of the *Report* deals with science and technology systems, describing the manner and means by which science is organized and carried out, and showing how indicators of scientific activity can be interpreted to give a global picture of science in the world.

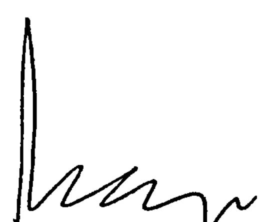
International cooperation, whether it be at inter-governmental or non-governmental level, is a major feature of science and technology today. Many scientific fields require extensive – and often expensive – research, and this can sometimes only be achieved by collective action on the part of governments, institutions or individuals. In Part 3, three exponents of such cooperation describe and discuss the many benefits and successes that have accrued from international partnerships.

No book claiming to be an account of the state of science in the world can avoid discussing something of the *substance* of scientific research. In an attempt to transmit some of the excitement of modern discovery we invited four scientists whose work keeps them in touch with developments across their disciplines to each write a readable, non-specialist account of just some of the significant developments in their fields during the course of the last two or three years. We trust that these chapters will be of interest to those not necessarily specialized in the respective areas, but wishing for such an overview. The number of subjects that could have been treated in this way was, of course, almost limitless. We were obliged to be selective and for this first issue have restricted coverage to the four basic sciences: mathematics, physics, chemistry and biology. In subsequent publications the applied sciences will be reviewed, including the earth and environmental sciences, engineering, and computer and information sciences.

The text of the *Report* is complemented by an Appendix containing statistical data on national scientific manpower and expenditure taken from the most recent issue of UNESCO's own *Statistical Yearbook*.

This report appears at a time when the need to boost the scientific input to decision-making – all too often based on exclusively economic and political considerations – has never been greater. Ways must be found of ensuring that the decisions of government and industry incorporate the best possible advice of the scientific community. Scientists are also required for other essential development functions, such as selecting, adapting and maintaining imported technology and staffing the new posts (e.g. the 'eco-jobs' required to implement Agenda 21) that must be created, particularly at the municipal level, to address some of the major challenges of our time (protection of the environment, rational use of water resources and management of non-renewable energy sources).

The publication of any document which purports to be a comprehensive and up-to-date report on a subject as complex as science and technology is a hazardous exercise. It is clear that some areas which might well have been included have had, for reasons of space, to be left for a future occasion. We nevertheless hope that this and subsequent issues of the *World Science Report* will be of use and interest to a wide audience, including decision- and policy-makers involved in science and technology matters, those researchers and teachers wanting an overview so often lacking, and individual non-specialists simply interested in knowing a little more about the state of science in the world today.



Federico Mayor
Director-General of UNESCO

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1 STATUS OF WORLD SCIENCE

INTRODUCTION

M.G.K. Menon

A distinctive feature of the present millennium of human history has undoubtedly been the birth of modern science and its subsequent exponential growth. Science has, of course, been an intrinsic part of human activity and of human society from earliest times. The sense of wonderment and curiosity about one's surroundings, coordination between the various senses and between the hand, eye and brain, the process of finding answers to questions, and the evolution of logical reasoning are all factors basic to the development of the scientific method.

The great centres of human civilization and culture, particularly in China, India, Mesopotamia, Central Asia, South America, Egypt, Greece and Rome, left us with important discoveries that were to underpin later scientific developments. However, during those earlier historical periods there were bursts of scientific activity without any consistent self-sustaining growth process. Then, a few hundred years ago, in Europe, the Scientific and Industrial Revolutions occurred and took root. Since then, the development of science has been gathering momentum but has flourished in only certain regions – chiefly Europe, North America and Japan. Due to internecine conflicts, feudal structures, a lack of tolerant and liberal attitudes, and colonial domination, the regions of the globe now known as the Third World fell behind, and except for occasional brilliant scientific work, still suffer from a lack of knowledge-based development.

This, the last century of the millennium has been characterized by an explosive growth of information, knowledge and understanding gained through scientific research. As a result of the technological application of this knowledge we have witnessed many ages occurring in parallel. Earlier periods of human history such as the Stone, Copper, Iron and Bronze Ages spanned prolonged periods of time. By contrast, the 20th century has seen the Atomic Age, the Space Age, the Age of Electronics and Informatics, the Age of New Biology, the Age of New Materials and the Age of Understanding the Organization of the Universe.

THE UNITY AND INTERDISCIPLINARITY OF SCIENCE

In the advance of science many individual fields have developed through extensive observation and the formulation of related theoretical ideas, and have a distinct character described by a phenomenology of their own. However, such fields, which were regarded as distinct and separate (and they may continue to remain so at some levels and for certain purposes) can be brought together in a common system of understanding.

Another aspect of great importance for the advancement of science is the manner in which different disciplines come together for mutual support and, more importantly, give birth to wholly new fields and disciplines. Mathematics and physics are today playing a profound role in chemistry, as are physics and chemistry in biology. Mathematics, physics, chemistry and biology are now being found to be critical to our understanding of the Earth system, particularly in the areas of the geosciences and ecology. It is through these interdisciplinary approaches that the revolutionary new developments in molecular biology, genetic engineering and biotechnology have all come about.

Besides the unity and interdisciplinarity among the natural sciences, there is increasingly closer interaction between the basic and applied sciences, especially in engineering, agriculture and the medical and veterinary sciences. It is these interactions which have led to the prodigious number of applications of scientific discoveries in products and processes in use in various sectors of society.

There is, however, one area of interdisciplinarity that has remained relatively weak, and that is between the natural and social sciences. The effective study of disciplines like geography, anthropology and psychology undoubtedly requires an overlap between the natural and social sciences; economics is acquiring an increasingly mathematical character and makes use of many conceptual advances from physics, chemistry and biological systems. But with the increasing permeation of science into society, it is of enormous importance that the interdisciplinarity that has been so productive in the natural sciences should also grow more profoundly between the natural and social sciences.

CHARACTERISTICS OF MODERN SCIENCE

During the last three decades, the scale of scientific advancement has increased almost out of all recognition. This is evident whether the scientific enterprise be measured in terms of the number of active research workers, the expenditure on science, the number of research publications or the extent of production in the world based on scientific advances. Such a signal change in the scale of activity cannot but call for a profound change in the character of science itself and in its relation to society. Science is no longer a stand-alone activity, at the fringes of society, but one closely intertwined with medical, industrial, agricultural and other production sectors, and with governmental and inter-governmental functioning, in such a manner and to such an extent that it pervades and affects society as a whole.

A second important characteristic of recent scientific development is the rapidity with which scientific discoveries are being put into practical use. While a proportion of production, particularly in the developing countries, derives from traditional practices, the major part of current production depends on, and can be immediately traced back to, scientific discoveries of the recent past. Increasingly these discoveries are of the 20th century, and frequently from the last few decades. Electronics and information technology, plastics and synthetic fibres, hormones and antibiotics, nuclear energy, space technology with all of its applications, and genetic engineering are areas which illustrate the manner in which fundamental scientific discoveries are rapidly translated to products and processes used in daily life.

A third feature has been the application of science to armaments. The interest of scientists and inventors in the machines of war, and in consulting for the military, is not new. Leonardo da Vinci, who is universally known for his prowess in the creative arts, was also a great scientist. In a letter to the Duke of Milan, to whom he offered his services, he dwelt extensively on his abilities in inventing the apparatus of war; indeed it was only at the end of his letter that he mentioned the skills he possessed as an architect, sculptor and painter which might be of use in times of peace. Leonardo recognized that there could be circumstances that might necessitate an involvement in military work. He said: 'When besieged by ambitious tyrants, I find a means of offence and defence in order to preserve the chief gift of nature, which is liberty.' But he was also aware that inventions could be used in ways neither originally conceived by nor to the liking of their originator. In commenting on his ideas for a submarine, he said: 'Now by an appliance many are able to remain for some time under water. How and Why? I do not describe my method of remaining under water for a long time ... and this I do not publish or divulge, on account of the evil nature of men, who would practice assassinations at the bottom of the seas by breaking the ships in their lowest parts and sinking them together with the crews who are in them.' He was thus opposed to the indiscriminate development of weapons of horror to be used purely for conquest and exploitation. And it is only during this century, with the use of aircraft, tanks and poison gases in the First World War, and radar, sonar, rockets and atomic weapons of frightening power during the Second World War, that science truly became related to the military enterprise.

Over the last half century the subventions to science by governments to prepare for new and ever more scientific wars has continued to be multiplied by large factors. From battles involving armies in close conflict, the scope of war has enlarged to involve the entire human population. And it is not only in the lethal weapons themselves, but also in the large support mechanisms needed for war that modern science has begun to be an essential part of the military system.

Until relatively recently, the concern was over wars involving nations and governments, with well-defined weapons systems. But the fact that many advances in the production of explosives, automatic and biological weapons can be exploited by small groups of people interested in anarchy and terrorism has added a new dimension to the terror to which science has contributed.

Science today enjoys a synergistic and symbiotic relationship with technology. In the early stages of technological development, progress was achieved largely through the use of skills and techniques acquired empirically; there was relatively little in terms of an intellectual understanding of what was involved. For example, one of the most remarkable inventions, and one which has had a significant societal impact, was the steam engine. It was not developed, as might be assumed at first, from an understanding of thermodynamics. Rather, such technological developments always involved new but simple ideas and an element of innovation. In recent decades, however, technology is moving forward through a basic scientific understanding of the processes involved. Electrical engineering, an important contributor to technology, was from the beginning wholly science based. By contrast, chemical technology was in its early stages largely empirical, even if now highly science based. Developments in fields like nuclear technology, biotechnology, space technology and information technology, are all based on scientific discoveries, knowledge and understanding. In turn, technological development is enabling science to move forward much faster. Powerful capabilities arising through the availability of new materials, electronics and instrumentation are facilitating more rapid and reliable scientific work. For example, computer technology is at the very heart of scientific activity and progress today. It is this close relationship between science and technology that is enabling each to progress so much faster.

CHANGES IN THE ORGANIZATION OF SCIENCE

Throughout the history of modern science a significant proportion of research has been carried out in educational institutions, a situation that persists even today. The greatest scientific discoveries have invariably flowed from the deep motivation, the sense of curiosity, the intuition and sheer intellectual power of individual minds. For these attributes to flower and bear fruit, an environment is necessary that allows the mind to roam freely over the intellectual horizons at the frontiers of current understanding. While the appropriate support structures are no doubt called for, the most important requirements are freedom of thought and expression, and a cultural background which nurtures scholarship. It is the young who are most original, being untrammelled by a vast amount of information and experience, but equipped with the technical skills necessary for front-line research.

Until the Second World War science was a leisurely activity carried out with modest funding, and frequently involved groups in which there was a highly effective teacher-student relationship. After the War science became more organized with much greater amounts of money poured into research. Large facilities and major research projects and programmes came into existence. The success of organized projects during the Second World War, such as the development and deployment of radar and the Manhattan Project for the development of the atomic bomb, had demonstrated the power of very specific mission-oriented activities. Industrial research laboratories which had existed well before the Second World War grew larger, and some moved extensively into areas at the frontiers of science, even of pure science. The Bell Laboratory is an example of an industrial research laboratory which has nurtured many Nobel prize winners. The transistor, which revolutionized electronics, was invented there. The experimental evidence for the microwave background radiation indicative of the whisper residual from the Big Bang at the birth of the universe, and which is certainly a measure of the temperature of the universe today, was also first reported from the Bell Laboratory. Indeed, radio astronomy could be said to have been born there. Nobel prize winning work has similarly been performed in many other industrial research laboratories.

Today, a very large part of the expenditure on science is incurred by industry; and by government, in areas such as defence research, the provision of infrastructural and surveying facilities, and large programmes such as space, meteorological and oceanographic research. In this setting, universiry research may appear to have been relegated to the background, and this may be so in terms of financial allocations, although it still continues to be the heartbeat of science.

THE APPEARANCE OF 'MEGASCIENCE'

Since the end of the Second World War major activities in science that involve multiple experimental locations, or a single complex and sophisticated laboratory whose installation and operation require large teams of scientists and an expenditure that is not easily borne by a single country, are conducted in the form of megascience (or Big Science) projects. These projects were initially in the areas of high-energy elementary particle physics and in the space sciences. Now they include other areas such as the earth sciences and modern biology.

In the case of high-energy physics the rationale for megascience projects is easy to understand. In exploring the structure of matter, the increasingly small dimensions involved require the use of probes with wavelengths of comparable dimensions. Since there is an inverse relationship between wavelength and energy, it is necessary to achieve increasingly higher energies to produce such probes. For this work giant accelerators have been used, as for example at CERN in Geneva, a collaboration which was initiated, and continues, as the effort of a consortium of European nations.

Satellites, launch systems and deep-space probe programmes are also usually of major proportions. Initially, satellites and space probes were launched exclusively by the USA and the former USSR. The European Space Agency, another consortium of European nations, Japan, China and India have all followed, albeit on a smaller scale. These projects are becoming progressively more expensive and are therefore being proposed as collaborative multinational efforts for the future.

The sequencing of the human genome is a project which arguably represents biology's first step into megascience. At present it is being dealt with by individual nations and therefore questions of intellectual property rights have arisen, although many believe that the Human Genome Project should be organized as an international collaborative venture. Some experts predict that the common features of the human genome will be mapped by the year 2000 and that individual genomic differences will be mapped soon after.

Many in the scientific community feel that with the increasing demands of resources for megaprojects, 'small science' may be starved of funds. A feared consequence is a distortion in the character of science, perhaps making it more organized and managed like industry, with the aim of accomplishing certain defined tasks. Such organization may, in fact, lead to a loss of that creative impulse which arises from the inner urges, motivations and originality of an individual. It is most important therefore, in this era of megascience, to ensure a balance with small science and research in educational institutions, where young scientists pursuing their own ideas continue to be supported.

RECENT CHANGES ON THE GLOBAL SCENE AND THEIR IMPACT ON SCIENCE

The momentous geopolitical changes of the past decade seem not to have been foreseen by even the most astute analysts of world events. For a period of four decades after the Second World War, during the era of the Cold War which was characterized by two superpower blocs in confrontation, the world witnessed an upward spiral of militarization with weapons of increasing sophistication and mass destruction capability being developed. The conflict between the two politico-economic systems then suddenly ended with the total collapse of the command structure of Central and Eastern Europe. Global restructuring and realignments are now taking place, leading to new economic groupings and strategic alliances. The prevailing economic picture today is one involving market forces, competition and the free flow of trade in goods and services, with minimal barriers in the form of tariffs and subsidies.

The impact of this turn of events on science is yet to be felt. One of the major hopes has been that with the collapse of one of the superpowers and the corresponding reduction in the level of military confrontation, there would be much less need for the large and escalating military expenditure that has characterized the post-Second World War period. This reduction in defence expenditure, the so-called 'peace dividend', would hopefully then be available for civilian purposes, particularly sustainable development, and in the process provide support for the undertaking of science as an innovative, creative and cultural activity of humankind.

At least two factors have prevented such a budgetary realignment being achieved. Firstly, the entire world has been in overall poor economic condition for the past decade. The great market economies of North America, Western Europe and Japan have been in a state of recession and rising unemployment. The economies of Central and Eastern Europe and the former USSR are in near-crisis. There are, therefore, no indications of any increase in assistance from the rich to the poor countries, nor of increased funding for science.

A second aspect whose importance is not generally appreciated, is that it is becoming increasingly difficult for governments to levy resources from their societies to finance activities which rightfully fall within the governmental domain. In other words, resources are vested in the people on a much more decentralized basis (and this is as it should be), although a significant portion of these are spent on consumerism. It is unlikely that the industrial enterprises that earn these resources would invest in pure science and basic research. In the current competitive market place, where the challenge for industry is to generate products and processes that sell, investment is more likely to be in applied research and technological innovation. The need is therefore to look for organizational methods whereby governments and large corporate entities can make resources available for science, particularly basic research, for cooperative global scientific efforts such as earth systems research, and other megaprojects of high priority, as well as for continually creating the infrastructure needed for science for it to fulfil its mandate as a creative manifestation of the human spirit.

THE DEVELOPING COUNTRIES' PERSPECTIVE OF SCIENCE

Among the countries of the developing world, some can boast of high per capita incomes due to their possessing a natural resource such as oil. The vast majority are poor, but cling to the notion that they can move along the pathways which the rich countries have trodden in the recent past and attain similar standards of living. With the information technology of today, particularly television, and the vast movement of people facilitated by mass air travel, each part of the world knows how the other lives. And so in the developing countries, with their large and growing populations, there is a rising tide of aspirations and expectations of the good life they see in the affluent countries, raising in turn the moot question as to whether the life-support systems of the Earth could carry the entire population of the world if it were to assume the high-consumption lifestyle currently seen in the North. In the first instance, it is more important to recognize that the poor countries of the South have to provide their populations with the basic needs for life and human dignity. And the pathways towards this development must be sustainable not only for the South, but for the world as a whole. Such development can be achieved only through the most intensive and appropriate use of the powers that science and technology have made available to humanity. The North will have to make its contribution by setting a good example of reducing its unnecessarily consumerist lifestyle. While the precise contributions of labour, capital and technology to socio-economic growth vary considerably in different situations, it is generally agreed that technology has accounted for most of the global economic progress in the recent past. It may also be argued that other factors that prevent the progress of development, such as population pressure and political instability, derive from a lack of development.

In the post-colonial era that followed the Second World War, there were many theories concerning the development process and the role of science and technology (S&T) in it. A feature that is increasingly evident is that development cannot be brought about from outside, but must have roots within the country concerned, and hence there is a need for an S&T capability which is endogenous. When a sound S&T infrastructure exists, external assistance acts as a powerful catalyst; it can be assimilated and judiciously used. Conversely, without such an absorptive capacity within a country, most assistance from outside tends to be wasted. The promotion of S&T in the countries of the developing world is therefore a must.

Despite the divergence of their economic policies for the major part of this century, the Western industrialized nations and the countries of Central and Eastern Europe share a somewhat similar scientific tradition in that they have participated in the forward march of modern science since the Industrial Revolution. As a result, science and technology are deeply rooted in their cultures. And now, this is also true of Japan.

By contrast, in the developing world there has been a lack of tolerance towards science. There has also been a lack of formal education for large segments of the population, who continue with their traditional work as in bygone centuries. Both these characteristics need to be changed, and literacy, universal elementary education and particularly science education need to be given very high priority on the national agenda. There is also a need to propagate value systems that would provide the pursuit of scholarship with a high degree of prestige in society. In the early stages, until business and industry are able to provide significant resources for research and development, the governments of the developing world, with whatever assistance they can obtain from abroad through overseas aid programmes and intergovernmental organizations, must allocate the necessary resources for education and capacity building in science. Only in this way can an endogenous base and an infrastructure for science be created and people equipped to participate in knowledge-based, innovative socio-economic development.

GLOBAL SCIENCE AND INTERNATIONAL COOPERATION

Scientists have always constituted an international community. As individuals, they have interacted and cooperated professionally across national and continental boundaries. This has been less true in the sphere of technology, since commercial and strategic considerations have precluded the free flow of information. More recently, this situation has changed on account of the high degree of global interdependence which is a distinctive feature of multinational enterprises.

In addition to collaboration between individual scientists or groups of scientists, there are now an increasing number of problems that call for international cooperation. First, there are the megascience projects which were mentioned earlier. Then, there are those which require international cooperation because the problems themselves are of a global nature, and demand extensive networks for observation, measurement and analysis. An early example of this was the mapping of the Earth's magnetic field, which required observations from numerous points on the surface of the globe. In today's context, questions relating to meteorology, oceanography and the Earth's environment in general are in this category. Such programmes presuppose a large infrastructure, with ships, aircraft, satellites, data reception, storage and analysis systems, and a very large number of observing points; furthermore, they require clear task definition, research allocation, phasing of programmes, organization and management, and coordination to ensure their success.

The International Council of Scientific Unions (ICSU) has played a key role in organizing international scientific activities, especially those relating to the environment, during the last half century. These activities have involved, in addition to individual scientists, intergovernmental and non-governmental organizations.

In order to support the large global environment programmes, major observation systems like the Global Climate Observing System, the Global Ocean Observing System, and the Global Terrestrial Observing System are being set up in collaboration with the World Meteorological Organization and UNESCO's Intergovernmental Oceanographic Commission (IOC). These systems are expected to complement the Man and the Biosphere (MAB) programme and the International Hydrological Programme (IHP), which are long-standing UNESCO initiatives.

These global programmes provide a unique opportunity for scientists in the developing countries to participate in front-line science because of the fact that the observations are to be made from numerous sites on the Earth's surface, many of which will be located in those countries. Participation in these programmes also has an important information-exchange and training dimension which facilitates the process of building up endogenous S&T in the developing countries.

SCIENCE FOR SUSTAINABLE DEVELOPMENT

Earlier in human history, when populations were small, the scale of human activities placed no irreversible stress on the Earth's environment. However, the world's population has grown from an estimated 300 million at the start of the present era to 1.7 billion in 1900, and is expected to reach about 6 billion by the year 2000. A saturation figure of between 8 and 15 billion may be achieved, depending on how rapidly population stabilization measures succeed. This population growth is taking place almost exclusively in the developing countries. Clearly, the minimum needs of human society, however populous, would have to be met in terms of food, shelter, clothing, water, energy, employment, basic education and health care. Development must therefore follow a model that will ensure the provision of these fundamental requirements. There has been an enormous increase in the scale of human activities since the Industrial Revolution; industrial production has increased by more than 100-fold. This has not been wholly at the cost of natural resources or of the environment, as some would believe, because science and technology have constantly provided new ways to make better use of resources by significantly improving productivity and efficiency, and bringing into use wholly new resources. Yet, we now know that the impact of this greatly enhanced scale of human activity is straining the Earth's life-support systems. As the developing countries with their large and growing populations nurture aspirations of the high living standards seen in the developed countries, as is but natural, and imitate their patterns of development, so the impact on the environment may turn out to be irreversible and may indeed jeopardize the continuation of human life on Earth.

The impact of human activities on the environment was initially of a local nature, taking the form of air and water pollution and deforestation. It then expanded to assume regional proportions, affecting more than one locality or nation. Acid rain, desertification, oceanic oil spills, industrial pollution of major river systems and the effects of nuclear and chemical accidents are no respecters of local and national boundaries. Further concern has been caused by recent scientific revelations of environmental degradation that is imperceptible to the human senses; stratospheric ozone depletion, and the rapid build-up of greenhouse gases that has the potential for global warming which could trigger climate change and sea-level rise, are phenomena with serious implications for human life. These global environmental effects will have to be dealt with by all sectors of human society acting in a common interest.

The consumption patterns of affluent modern industrial societies which are sustained by the advancement of science and technology, and the high population growth rates in developing countries, are clearly the two major causative factors of environmental stress.

Population stabilization in the developing countries can only be achieved through rapid human-centred development. The problem before us is to ensure that developing countries continue to develop, but along pathways which are sustainable in the long run. As brought out clearly in the Report of the World Commission on Environment and Development chaired by Mrs Gro Harlem Brundtland (and known colloquially as 'the Brundtland Report'), sustainable development 'must ensure that it meets the needs of the present without compromising the ability of future generations to meet their needs'.

In the late 1960s the Club of Rome produced a report entitled *Limits to Growth* which considered whether humanity could afford to continue its current growth pattern with its demand on resources, and whether limits on resource availability would put severe constraints on the potential for growth. The question before us today, in the context of the need for continued development, is not so much in relation to the availability of resources, but the capacity of the life-support systems of planet Earth to absorb the anthropogenic impacts that our current lifestyles and patterns of development are producing and which are due to increase with time. The emphasis has thus shifted from mere resource conservation to environmentally sound sustainable development.

While many solutions undoubtedly lie within the domain of science and technology, environmentally sound sustainable development cannot be brought about through a purely technological fix. There is also a need for society to understand and accept the need for a change to a new way of life and living. We are thus faced with the problem of formulating conclusions and recommendations in a manner that governments, people, business and industry can accept and act upon.

In addressing policy and decision makers, scientists must simplify their thoughts, use plain language, abandon various qualifications in their recommendations, and indeed commit themselves to viewpoints in areas where there is a fair degree of certainty. On the other hand, politicians operate on shorter time-scales defined by processes such as elections, and would prefer to proceed along well-beaten pathways which are known to yield tangible results rapidly. Longer time horizons involving intergenerational equity would not be within the time-frames of their action plans. It is therefore important that those in the natural sciences and technology come together with social scientists, businessmen and industrialists, politicians and decision makers, within and outside government, as well as with those concerned with the development processes and with society at the grass-roots level, to evolve a whole new interactive process of education, awareness building, analysis and decision making. Further, the terminology currently in use, such as growth, development, gross national product and cost-benefit analysis cannot continue to be used on the basis of their narrow definitions; their meaning will need to be reconsidered in terms of the situations that will be encountered in the future. We will need to recast parts of our educational systems to promote a better understanding of the environment and to instil value systems which enshrine the principle of sustainability over generations.

It must be recognized that the Earth's carrying capacity is finite and that a certain harmony or balance between human populations, their activities and the rest of the living and non-living systems on the planet must be achieved. One population cannot be continuously growing at the expense of another. The question may then be raised as to whether such a state of harmonious existence can be stable or whether it will decay. The answer is that there must be continuous change; a dynamic equilibrium must be attained that will lead to a better life through new methods of using resources rather than overexploiting some or a large part of the Earth system. Science and technology can be an enormously powerful force in devising innovative ways of utilizing the same resources, but these methods have also to be acceptable to society. This is the challenge and task before us as we seek new directions for science that are likely to yield an improved quality of life for all.

UNCED AND AGENDA 21

The United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro, Brazil in June 1992, derived its *raison d'être* from the Brundtland Report, published a few years earlier. That report called for a process of development which would be sustainable, and in harmony with the life-support systems of the Earth and with its carrying capacity. It placed development in a context that went far beyond economics alone; development had to ensure equity within the present generation as well as between generations. It focused on the need to change course, from the present patterns of development and consumption, if sustainability were to be ensured. UNCED, held following significant preparatory work, was *the* effort to discuss these issues at the highest intergovernmental level.

The centrepiece of the discussions in Rio was clearly Agenda 21. This is essentially a very broad-based programme of action covering developmental and environmental issues dealt with on an integrated basis. It is important to recognize that Agenda 21 was negotiated by governments paragraph by paragraph, sentence by sentence. ICSU helped in the preparation of Chapter 35 of Agenda 21, entitled 'Science for sustainable development'. Apart from this specific chapter, science has a very important role to play in addressing many issues dealt with in other chapters such as those on protection of the atmosphere, planning and management of land resources, oceans and freshwater resources, conservation of biodiversity, environmentally sound management of biotechnology, combating deforestation, managing fragile ecosystems and management of toxic chemicals, hazardous and radioactive wastes. Chapter 31, 'The scientific and technological community', elaborates on the desired collaboration between science, policy making and public information, Chapter 36 on promoting education, public awareness and training, and Chapter 37 on national mechanisms and international cooperation for capacity building in developing countries. The last is especially of relevance to the scientific community because S&T capacity building is an essential ingredient in bringing about sustainable development.

AGENDA FOR SCIENCE IN THE CONTEXT OF UNCED

Of utmost concern to the scientific community is the agenda for science that can be enunciated in the context of the intergovernmental consensus arrived at in Rio. Broadly, this agenda can be categorized under three headings:

To apply, with a sense of urgency, what is already known and can ameliorate environmental stress to a significant extent in many areas; scientists, in association with social scientists, business and industry, policy makers in government and non-governmental organizations must examine the impediments to such application, and devise means of overcoming them.

To develop new approaches, particularly in crucial areas where environmental stress due to anthropogenic effects cannot be easily reduced or done away with, because of the need to meet human needs and aspirations.

To develop programmes to understand the Earth's environment, so that one has a baseline concerning the many parameters that are likely to change over a period of time due to human activities; one can then monitor the changes as they take place and produce an assessment of their implications well in time for preventive action to be initiated. Observations on a continuing, global, synoptic basis need to be followed by analyses of how these data interrelate in the complex systems that constitute the Earth's environment. Thus the development of a whole new era of interdisciplinary science, 'earth systems research' is required.

ETHICAL ASPECTS, HUMAN RIGHTS AND THE PUBLIC IMAGE OF SCIENCE

As science and technology move forward at a dizzying pace, their power to affect human society for better or for worse has increased. Ethical considerations, questions of human rights and the image of science in the public mind are therefore issues causing increasing concern. Given the breadth of the subject, it is only possible to discuss here some illustrative examples of the type of problems that may arise.

First let us consider issues emerging within the practice of science. As scientific work results in outputs that may be protected under intellectual property rights, matters relating to the freedom of information, particularly the right to freely discuss scientific issues, and to communicate within the scientific community, are coming into question. While there have been disputes in the past concerning the parallel development of ideas or of discoveries, controversies and legal wrangles on priorities are much more commonplace today. These, and commercial as well as strategic and defence interests, are leading to a situation of secrecy rather than openness in scientific pursuits. Hoaxes, plagiarism and reluctance to acknowledge original sources or assistance are being reported in the press, and public investigations of these are becoming an unfortunate feature of the scientific scene.

For a long time now, advocates of animal rights have protested against the use of animals for scientific experiments involving pain or their sacrifice. Some of the arguments are indeed entirely appropriate, since in exceptional cases there has been excessive animal experimentation and callousness in animal usage. One of the counter-arguments of those who consider careful animal experimentation necessary is that, in the long run, the results of that research will benefit very large numbers of humans and perhaps animals themselves.

In the new biological sciences, many ethical and social issues of immense complexity are being raised by activities such as the Human Genome Project and its associated programmes. Should there be ethical limits to the investigation and manipulation of human genetic material and use of information so derived? Should there be genetic manipulation of human reproductive cells and experimentation on embryos? Would the genetic inheritance of humanity be dangerously modified by such experimentation? Would the effort to decode the human genome diminish our humanness? Would it be possible to prevent the engineering of 'desirable' traits in future generations? Even though genes are the very core of our being, link us with the past through evolution and determine our future, what are the roles of education, the environment and cultural factors in shaping the human being? Are we helpless products of genetic directives without freedom and responsibility for our actions? Should genetic material be used by the police and in forensic science? The use of eugenic information in coercive social politics and as a means of discrimination has not entirely disappeared. These and many other such questions are coming to the fore as the study of human genetics probes ever deeper.

The power of contemporary information technology is also raising certain ethical considerations. These concern the invasion of personal privacy and the collection of information in various ways at various times which may later be used to discriminate against individuals or groups of individuals.

Concerning the image of science, Bishop has stated:

'We live in an age of science, when many of nature's great puzzles have been solved. The fruits of science have vastly improved human welfare and understanding. Yet science now finds itself in paradoxical strife with society: admired but also mistrusted; offering hope for the future but also creating ambiguous choice; richly supported but unable now to fulfil all its promise; boasting transcendent accomplishments but criticized for not serving more directly the goals of society.'

CONCLUDING REMARKS

In concluding I wish to focus on two issues which I think stand out as being those that hold the most serious implications for the future of humankind. They are issues that contemporary science can, and must, address with a sense of the utmost urgency. Firstly, the world's population will grow, chiefly in the developing countries, to a figure well above 8 billion before stabilizing, perhaps at a figure of between 8.5 billion and 15 billion according to demographic projections. In order to achieve a stable equilibrated population at the lower end of the projected range, development and poverty alleviation programmes must be executed rapidly and effectively. The world will then have to learn to live with its population and to meet its basic needs equitably.

Secondly, the total energy consumption in the world is set to increase to more than twice the present level. Current estimates indicate that a maximum requirement level will be reached at between 22 and 26 terawatts (1 TW = 10^{12} watts) per year. The major source of this energy will continue to be fossil fuels; there is no other efficient and acceptable source of large-scale energy generation on the horizon. And because the world will have to live with higher CO_2 emission levels, extensive scientific work must be undertaken to understand with some certainty what environmental effects will result. There will also be a need to devise processes for trapping or destroying greenhouse gases and to carry out intensive research on new energy sources.

Population and energy are but two issues. There are in addition a vast number of related problems that need to be solved in order to provide the world's population with its minimum needs and to meet the basic requirements of human dignity. Thus, while science must continue to flower as humanity's great creative and cultural activity, it must also be managed to meet societal needs and expectations.

Yet it must be acknowledged that science and technology by themselves do not offer solutions to the majority of our present socio-economic problems, in contrast to the views of some in the scientific community who believe that technology alone holds all the answers. The more broadly accepted conclusion is that the solutions we are seeking will involve, besides S&T, political, economic and social considerations. Science and technology must therefore build bridges with society and tend towards greater interdisciplinarity.

Science and technology today are enormously powerful forces but science and scientific education have, in their own right, no concern with moral and spiritual values. It is therefore incumbent upon scientists to ensure that as science and technology progress, their power is tempered with restraint and wisdom. Surely science, no less than other cultural endeavours, must enrich human life, not demean it. But in my view, while science tempered with wisdom may yet steer us to a brilliant future, no amount of wisdom without science can solve the socio-economic problems of today's world.

M.G.K. MENON is President of the International Council of Scientific Unions (ICSU), the foremost international non-governmental organization representing the science community. He is also a serving Member in the Upper House of the Indian Parliament.

Professor Menon received his education in physics at Bombay University and the University of Bristol in the UK. He joined the Tata Institute of Fundamental Research as a Reader and rose to be its Director. He set up the Electronics Commission and was its Chairman as well as Secretary in the Department of Electronics of the Government of India. He has also been Secretary to the Government of India in the Department of Defence Research, Environment and Science and Technology; he was Chairman of the Indian Space Research Organization, Director-General of the Council of Scientific and Industrial Research (CSIR), Member of the Planning Commission and Scientific Adviser to the Prime Minister of India. He was his country's Minister of Science and Technology and of Education during 1989-1990.

NORTH AMERICA

Rodney W. Nichols and J. Thomas Ratchford

HIGHLIGHTS

The shorthand phrase 'Science in North America' encompasses efforts in Canada, Mexico and the USA that focus intensively on research and development (R&D). These heterogeneous activities involve both the public and private sectors. Annual R&D spending in 1990-92 totalled about US$165 billion, serving almost 400 million people, with a combined gross domestic product (GDP) of about US$6 trillion, and spanning diverse national as well as international goals and markets. The North American grouping is arbitrary – given the substantial differences in resources, infrastructure, population, language, and other factors – and thus may be less meaningful than groupings in other regions. Nonetheless, connections are growing between the three countries and common themes are emerging.

Research opportunities

The enormous amount of scientific progress in recent years has served to engender robust new opportunities for research. For instance, frontiers in oceanographic and atmospheric sciences, and efforts from ecology to industrial engineering, are a high priority as global consciousness focuses on protecting the environment. Similarly, for improving the health of women and children, for understanding the brain, and for coping with the diseases of the aging, not to speak of conquering AIDS, vigorous and productive research proceeds throughout the life sciences and, emerging from the same base of biological research, biotechnology is likely soon to revolutionize agriculture. The information revolution also continues to bristle with advances in condensed matter physics, electronics, computers, software, and the telecommunications systems that build 'information highways' across every home, office and national boundary. Age-old puzzles about the origin of the universe, and many other problems in basic research, some esoteric, are yielding to powerful new concepts in physics and mathematics.

Such opportunities convince most of the public as well as government officials that science and technology (S&T) – especially at the basic level conducted most frequently at or with universities – have almost boundless intellectual, social and economic potential. Most private firms also see great business opportunities deriving from new and improving technology-based products and services that justify private investments throughout North America.

Restraints

Yet two important restraints slow initiatives to pursue these opportunities in the aftermath of the Cold War. One is the growing cost of carrying out first-rank science. Governments alone cannot finance the activity and large firms, faced with stiff competition, are reluctant to make large and long-term investments in R&D with uncertain payoff. This squeeze – the hard choices that inevitably must be made when opportunities exceed resources – has been seen recently in both Canada and the USA, especially in the light of the already large R&D base and difficult economic circumstances.

A second restraint comes from the fear that renewed emphasis on short-term economic and social applications will be pursued at the expense of longer-term investments in basic science. The aim to reap more quickly the benefits of research appears in all three countries. Research executives sharpen their focus on specific technical and scheduling targets. Investigators, especially in curiosity-driven 'little science', respond more frequently to near-term governmental or corporate goals.

All sectors suffer under these restraints. Strapped for resources, governments aim to mesh their strategies for support of S&T with their pursuit of national economic goals. The vitality of R&D in the academic community and in the private sector depends upon a mix of public and private support for R&D, and hot controversies surround the assessments of what mix will work best.

Canada

Tight budgets complicate Canada's desire not only for broader geographical distribution of research centres but also for increased effectiveness in mechanisms designed to push research results into improved economic performance. Governmental institutions in Canada have recently been changed substantially and others are in transition. For example, the key science and technology unit in the External Affairs Department responsible for the S&T network abroad has been abolished. The Science and

Economic Councils have been disbanded. One reason put forward for the changes, beyond cost-cutting, was to integrate S&T policy competence within the industrial and economic policies of government. However, there is also a concerted effort to maintain funding for the excellent groups long recognized in Canadian science. One newer path is to emphasize building networks for communications and research collaborations among centres of excellence within Canadian institutions and other centres around the world.

Mexico

A high priority has been placed in Mexico during recent years on science and technology. After a sharp downturn in spending for R&D during the early and mid-1980s, governmental support for research recovered and new advisory arrangements were established. As in Canada, Mexico is strongly concerned with both establishing a broader base of science and linking that base to the national potential for economic growth. Mexico is also developing new communication systems for connecting its national research centres with each other and with their counterparts throughout the world. As trade and economic growth proceed, private investment in research and development may well accelerate to match governmental support.

The USA

Previously high growth rates in support for science in the USA have stalled, and there are few prospects for the already large investment to increase rapidly in the future. The US Government has been using new high-level mechanisms to manage S&T budgets across agencies and to craft special initiatives for public support, such as, for example, in high-performance computing and in global climate change. Links between public sector research and national economic goals are being emphasized. The strong US investment in biological and medical research continues, but with abated growth. Defence research and development is decreasing. Commercially relevant research, sponsored by government, is increasing while corporate support declined during the recent recession. Vigorous debate proceeds about the comparative priorities and rising costs of 'Big Science' and technology, such as the space station and the superconducting super collider.

Common themes

Among all three countries, the most important imperative emerging for 'science policy' is national economic competitiveness. Even when discussing policies for basic science, the emphasis on jobs, economic growth and international economic competition has grown in significance; the effects of these concerns are unmistakable. One consequence is that 'technology policy' – such as revealed in the goals for new materials, diffusion of manufacturing know-how and advances in biotechnology – is a central feature of planning by governments in North America.

Another common theme is the increasing internationalization of research efforts. This includes: enhanced work on global information networks; increased cooperation in understanding the natural environment; greater attention to intergovernmental negotiations and consultations about intellectual property rights as well as about 'Big Science'; and broader use of cost-saving industrial R&D alliances within countries, between countries, and among national firms and governmental agencies. This powerful trend pressures both research-intensive national groups to become more international, and foreign ministries and international units to become more literate about science and technology.

In short, all three countries in North America now see S&T as even more critical to national progress than in the past. Accordingly, funding will probably grow over the 1990s whenever and wherever economic conditions permit. Yet the roles of science and technology are changing with new social and economic demands, and these changes will be reflected in both public and private investments. All three countries are also aware that as every nation must be even more selective about its investments in science, each will aim both to contribute to and to draw upon the global base of research.

Scope and limits of review

The following discussion takes an expansive definition of R&D throughout the public and private sectors. Owing to space limitations and to the division of topics in the *Report,* little attention is given in this article to specific frontiers of science. Instead, the emphasis is on policy, funding and institutional arrangements. Only passing attention is given to comparisons with other regions. Strictly comparable statistics are patchy for North America as a whole and there are small but persistent differences between the Organization for Economic Cooperation and Development (OECD), UNESCO and national sources; for the purposes of this review, these differences are inconsequential. It has become clear, however, that improved international cooperation will be needed to provide consistent and timely data for the purposes envisioned by the UNESCO *Reports*. Pioneering work by the National Science Foundation in its biennial *Indicators* publication, and the OECD in setting standards for collecting statistics, are models for what the world community should do.

WHAT THE PUBLIC THINKS

In the political realm, there is a saying that truth is not important, only its perception. If this is even partially correct, and if one accepts the definition of science as the 'habit of truth', then what the public thinks about S&T – and about scientists and engineers – is very important to the public policy process.

Importance of public attitudes

Public attitudes toward science are important to scientists and engineers as well as to the general public. Public perceptions and opinions affect the actions of legislators in funding research and education budgets, and condition the decisions of the private foundations and companies that support R&D. More importantly, public attitudes toward science affect acceptance of those new technologies that make us healthier and richer or, in some cases, pose risks to people or the environment.

There are substantial survey data on public attitudes toward S&T in the USA, going back to the 1950s. Publics in Canada and in the USA are generally similar in attitudes, but there is little survey data on Mexico.

US public supports science

The US public feels overwhelmingly that 'the world is better off because of science'. In 1957, in a survey carried out before the launch of Sputnik by the USSR, 88% agreed with this statement. In a 1988 survey, responding to the same statement, 88% again agreed.

Compared to other occupations and institutions, US scientists are near the top of the pyramid as far as public confidence is concerned. Further, about four out of five Americans feel that high-school students should have four years each of mathematics and science in their curriculum.

Approval of S&T in the USA is substantially greater than in most other countries. European nations lag behind the USA, and Japan's approval of science is the lowest in the industrialized world.

Concerns on the horizon

This does not mean there are no storm clouds on the science and technology horizon. Opposition to the application of new technologies and to new concepts in science stretches back for many centuries. In the 19th century Charles Darwin's ideas were rejected by many, and even today a substantial fraction of the US population does not accept evolution as a scientific fact. Ned Lud, a late-18th century English worker who destroyed textile machines, gave his name to the Luddites – a name still used for those who oppose applications of new technologies.

But there are also many thoughtful citizens, including scientists, who are concerned about the possible unintended secondary and tertiary effects that might accompany the widespread application of new technologies. This concern, expressed through the political system, resulted in the establishment in 1972 of the Office of Technology Assessment (OTA) of the US Congress. Since then the OTA has developed a justly deserved reputation for publishing thorough and reliable technology assessments that contribute to the integrity of the decision-making process for a wide spectrum of issues that are based on science and technology.

Biotechnology is just beginning to make its contributions to human health and the world economy. Its potential for improving agricultural productivity is great, but many citizens in the USA and in other countries have ethical and safety concerns about the use of biotechnology in food production. Although, as noted above, the interest in and support for S&T in general is very high, only two-thirds of the US public support the use of biotechnology in agriculture and food production. There is lower acceptance of biotechnology for modifying animals, than for modifying plants. Concerns are emotional, ethical, religious and moral, as well as economic. Many members of the public worry about the possible environmental impacts of biotechnology, including changes in the natural environment and negative effects on fish and wildlife.

In Canada, recent reports on privacy and guidelines to control the release of personal information show the concerns over the impact of technology on society. The report of a three-year Royal Commission on New Reproductive Technologies will be released soon.

Extensive surveys in the USA show that people with an interest in S&T, and who are scientifically literate, are more likely than others to support the funding of research and the application of new technologies, as summarized in Table 1. In practice, citizens with more formal education in general, and more formal training in science in particular, overwhelmingly conclude that the benefits of scientific research outweigh its harmful potential. For genetic engineering, nuclear power and space exploration, the margin is smaller, with the well educated public being substantially more supportive than others.

Moral and religious concerns also affect attitudes toward S&T among the US public. More than half of American adults either reject or are uncertain about the theory of evolution. And a 1990 survey showed that 45% of US adults were not convinced that animals like dogs and chimpanzees should necessarily be used in laboratory research.

These concerns about science and research among the general public reinforce the importance of increasing scientific literacy. Only a public that is literate and attentive to S&T can debate complex issues rationally and then develop effective policy strategies for dealing with them.

The integrity of science

The integrity of researchers has also come under scrutiny recently in the USA. Several cases of scientific misconduct involving fabrication or falsification of research results, or plagiarism in publication, have received extensive coverage in the news media and attention in Congress. Researchers with potential conflicts of interest of a financial nature have also been criticized. In response, the scientific community has given substantial attention to ensuring the integrity of the research process. Universities and government agencies involved in the support and performance of publicly-funded research are developing guidelines, including greater disclosure of potential conflicts, to deal with these problems.

Another concern relates to the use of scientific expertise in judicial proceedings. One issue is whether expert testimony of a scientific nature may be presented, as such, if it does not meet the usual validation criteria for scientific communications. The question of recognizing 'junk science' on an equal footing with traditional reviewed scientific studies is of major concern to many scientists and scientific organizations.

TABLE 1
US PUBLIC'S ASSESSMENT OF BENEFITS (B), RISKS (R) AND COSTS (C) OF RESEARCH AND SELECTED TECHNOLOGIES

	On balance research is		Genetic engineering risks & benefits		Nuclear power risks & benefits		Space benefits & costs	
Educational level	Beneficial	Harmful	B>R	R>B	B>R	R>B	B>C	C>B
Less than high-school graduate	47%	20%	42%	31%	41%	36%	35%	47%
High school or some college	74%	13%	45%	41%	46%	45%	42%	49%
College graduate	88%	4%	54%	29%	54%	38%	52%	39%

Sources National Science Board, 1991 and Miller, 1992.

FIGURE 1
US R&D EFFORT, 1992

Total national spending US$157 billion
Percentage of GDP 2.8%

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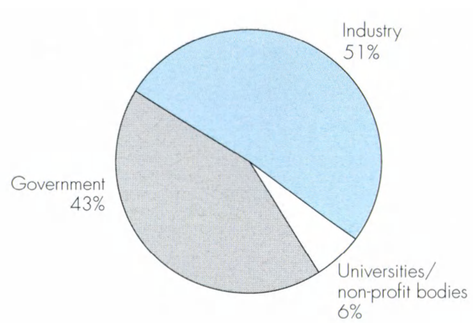

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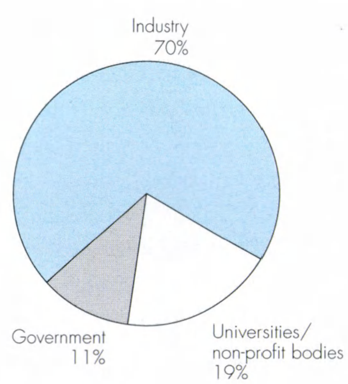
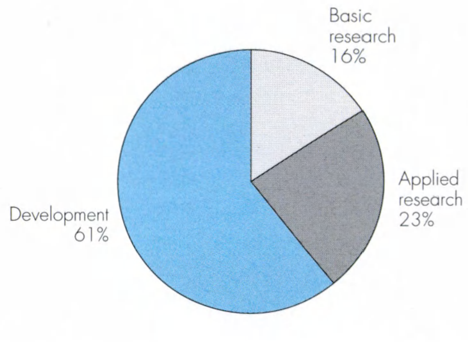




Source: National Science Foundation, October 1992, NSF 92-230.

'What you know affects what you think' is shown by the attitudes of the 'scientifically literate' public compared to the attitudes of other Americans on issues such as the benefits of funding research. But it is also true that 'what you think affects what you know'. That motivation affects learning is not a new concept. It is interesting, however, to observe the correlation between scientific literacy and age. For most countries, this is an inverse relationship: younger adults know more science, on average, than their elders. In the USA, however, in 1990, the 35-44 year old cohort was found to be the most scientifically literate. These were the young people who received their education during the years following the launch of Sputnik.

INVESTING IN SCIENCE

This section highlights the contours of expenditure on research and development, as well as the major performers of research.

Overall R&D expenditure

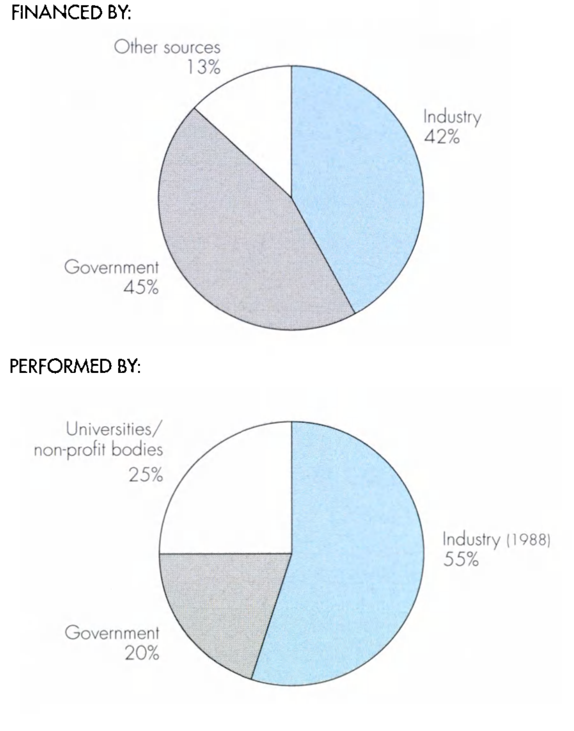
For the USA, Figure 1 portrays the overall 1992 investment in R&D, including basic science. The period 1985-92 had a slower growth rate in constant dollars (about 1% per year) than the period 1975-85 (about 5-6% per year, caused mainly by growth in life sciences research and defence technology). Industrial R&D spending has grown slowly in recent years, while academic spending has risen more quickly. The proportion of GDP spent on all R&D dropped slightly from 2.8% in 1985 to 2.6% in 1992.

For Canada (Figure 2) and Mexico (Figure 3), similar data show the patterns in 1991. Definitions differ between countries, and data for different years are the best information available; so direct comparisons across the region are not possible. The most dramatic recent changes in North America have occurred in Mexico: after falling during the early 1980s, sharply increased investments in science have been made recently, and total spending rose by 20% or more each year since 1988.

Table 2 gives comparisons among the three countries, drawing upon national, World Bank and OECD data. These diagnostic indices alone are sufficient to show the relative R&D intensity among the three countries, as well

FIGURE 2
CANADIAN R&D EFFORT, 1991

Total national spending US$7.5 billion
Percentage of GDP 1.4%

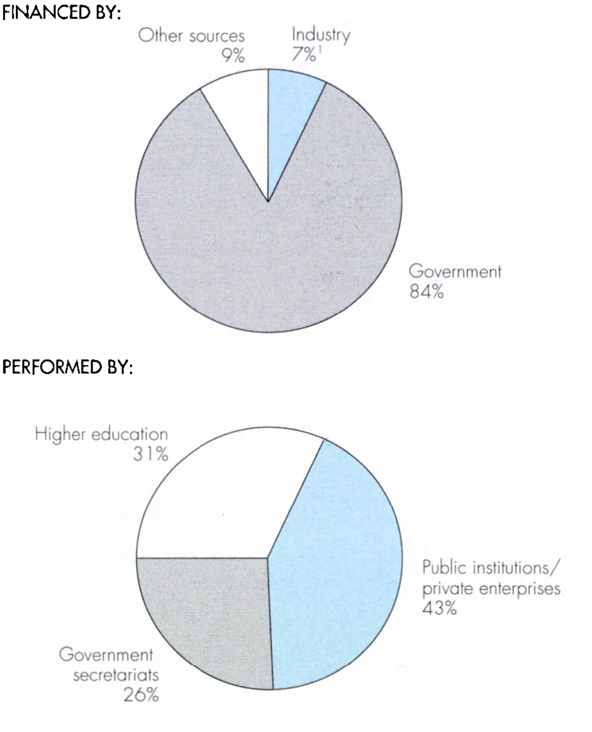


Note: spending in purchasing power parity (PPP) $.

Source OECD, 1992.

FIGURE 3
MEXICAN R&D EFFORT, 1991

Total federal spending US$1.1 billion
Percentage of GDP 0.4%



1. Preliminary recent data indicate that industrial investment in R&D grew sharply between 1989 and 1992.

Source: CONACYT, 1992.

as the roles of industry and universities, in the context of total population and GNP. For instance, these data suggest that the more industrialized the country, the more R&D-intensive is the economy and the more private firm-oriented is the R&D activity.

Human resources and NGOs

To help gauge human resources – the bedrock component of scientific and economic development – Table 3 compares the number of scientists and engineers, and the number who work in R&D per 10 000 in the workforce, with benchmarks elsewhere. The number of Mexican graduates in S&T increased substantially over the period 1986-91. As fellowships also increase, many Mexican students are being educated in the USA and Canada, thereby contributing to the process of bringing together the North American region.

The USA continues to receive an enormous number of

TABLE 2
SELECTED COMPARATIVE INDICATORS, 1990-92

	USA (1992)	Canada (1991)	Mexico (1991)
Total R&D spending (US$ billions)	157	8	1
Total R&D as % GDP	2.7	1.4	0.4
% total R&D			
financed by industry	51	42	7
performed by industry	70	55	na
% total R&D performed by universities and non-profit bodies	18	25	31
Population (1990) (millions)	250	27	86
GNP/capita (1990) (US$ '000s)	21.8	20.5	2.5

Sources: as for Table 1 and Figures 1 and 2, plus World Bank, 1992.

TABLE 3
SELECTED DATA ON HUMAN RESOURCES

	USA (1989)	Canada (1988)	Mexico (1991)
Total R&D scientists and engineers ('000s)	950	63	10
Scientists and engineers in R&D per 10 000 labour force	76	46	5

Scientists & engineers in R&D per million population, 1990

North America	3 360
Latin America and Caribbean	365
Europe	2 210
Africa	120
Asia	400

Sources: NSF 92-330; CONACYT, 1992, OECD, 1992; UNESCO (1991) *Statistical Yearbook*, Paris.

foreign students (400 000 in 1991), especially in science and engineering. In 1990-91, a total of about 18 000 Canadians and 7 000 Mexicans were studying in the USA (all fields). While overall data on science-intensive human resources are difficult to gather, in North America, as in other regions, it is clear that investments in education at all levels – and in the diffusion of knowledge from research and technology – are indispensable for enhancing productivity and economic growth.

Non-governmental organizations are an enormous source of vitality and diversity in science and education as well as in debates on policy issues related to science and technology. Especially in the USA and increasingly throughout the world, these organizations – ranging from professional societies to academies – provide networks for communications and private advice on public choices in fields such as energy, education and ethical guidelines for research.

Trends in support

While there is increasing emphasis in all three countries on applied research, support for basic research is being held more or less constant in real terms. Similarly, investments in science are increasingly dominated by civilian goals in terms of national social concerns (e.g. energy, communications, the environment) and international goals (e.g. markets for comparatively high-technology products and international cooperation in costly areas of science).

Sharp differences emerge between the three countries in support for different fields of science. For example, in the USA, as shown in Table 4, investment in the biological and medical sciences has grown extremely rapidly. Two decades ago, the total funding for physical and engineering sciences in the USA was much greater than the total support for life sciences; now the fields are funded at about the same level. It is significant that the enormous growth in the information industries was financed largely by the private sector; note that government funding for mathematics and computer science was roughly static.

For Canada and Mexico, similar trends seem to be emerging. Mexico has paid special attention to the environmental sciences, tripling the funding between 1987 and 1991. Canada has sustained through its three University

TABLE 4
US GOVERNMENT FUNDING FOR BASIC AND APPLIED RESEARCH BY BROAD FIELD (constant 1981 US$, billions)

	1969	1979	1989
Life sciences	3.7	4.9	6.8
Environmental science	1.1	1.5	1.7
Maths/computer science	0.3	0.3	0.5
Physical science	2.5	2.3	3.0
Engineering	3.4	3.3	3.3
Social science	0.6	0.7	0.5
Total	**11.0**	**13.0**	**15.8**

Source NSF, OTA.

Councils a blend of work across the physical/engineering, biomedical and social sciences.

US military R&D: change and conversion

The three countries differ sharply in their historical and ongoing involvement with defence research. In the USA, for many years military research and development accounted for more than half of the total governmental investment in R&D. Although this fraction has been declining for several years, and is expected to decline further in the future, the effort will continue to be a significant component of R&D in the USA. In Canada, military R&D has been a much smaller fraction (about 8%) of the overall research base and has been integrated with the civilian R&D base. In contrast, Mexico has virtually no military research sponsored by government.

TABLE 5
DISTRIBUTION OF US FEDERAL R&D, 1992

Function	% total R&D	% basic research
Defence	59	9
Health	14	41
Space	10	12
Energy	4	7
General science	4	20
Other (inc. environment and agriculture)	9	11

Source: NSF, 1992a.

Table 5 shows the 1992 US governmental funding for defence R&D in relation to other functions. The 1994 budget request from President Clinton continues the trend toward moderate defence R&D spending, with a cut (in constant dollars) that includes an unexpectedly large decrease (about 5%) in funding for basic science.

Along similar lines, the USA space budget has been under heavy stress during 1993, with tense national and international debate arising because of the added costs and extended schedule for building the space station. As a result of such pressures, a major reappraisal is underway in both the Department of Defense and NASA about long-range strategies for spending on R&D. The results of the reappraisal will affect the more basic efforts in space science.

Although decisions on defence and space R&D will not have a major impact on the USA's general policy commitment to science, the resulting swings could lead to sharp changes in funding for research and development involving many traditional performers. The impacts of budgetary changes caused by defence conversion will be felt in all of the government's inhouse laboratories and in a number of national laboratories that are operated either by or under contract to universities – accounting for spending of more than US$20 billion per year. The impacts will also affect the high-technology firms largely supported by defence, energy and space programmes.

The so-called 'weapons laboratories' operated by the Department of Energy – Los Alamos, Livermore and Sandia – have been under review for several years with respect to their missions, budgets and staffing in the light of changing national security goals. One possibility is to convert a portion of each laboratory's programmes into efforts directly related to collaborative work on environmental and other civilian problems with industrial and local governmental groups. Because each laboratory employs about 8 000 staff with budgets of US$1 billion, any such shifts in mission and resources are substantial, and cause economic dislocation. In effect, the USA will be undertaking a large experiment in the transfer of technical and human resources.

Comparisons with post-Second World War transitions, and with the sweeping changes in the former USSR and in Eastern Europe, are being made amidst much scepticism. Some observers doubt whether any long-standing governmental laboratories can adapt fully and quickly enough to establish new incentives and redeploy their great talent to fulfil market-oriented and/or civilian tasks. As a part of this overall transition, the Advanced Research Projects Agency in the Defense Department launched in 1993 a new US$500 million competitive programme designed to facilitate defence technology conversion with an emphasis on 'dual-use' R&D (i.e. technical projects appropriate for both economic and national security objectives).

SCIENCE IN THE UNIVERSITIES

Most countries support research in special centres; some are free-standing and supported largely by government, others are located on university campuses with highly diverse sponsors complementing government. Among the three countries of North America, the USA has tended to concentrate its basic science in universities, whereas Canada and Mexico have taken a more diversified approach. This section outlines the available data on funding for R&D in universities as well as several related policy perspectives.

US research-intensive universities

A major reappraisal is underway in the USA regarding the scope, level, priorities and geographical distribution of support for science at academic institutions. The long history of US emphasis on research combined with higher education has been matched by increasing financial investments (about US$19 billion for R&D in 1992). After tripling the scale of academic R&D over 30 years, there are now about 150-200 major research universities in the USA, two-thirds being state institutions and one-third private, together accounting for about 90% of all academic R&D.

In 1992, the President's Council of Advisors on Science and Technology documented the academic research trends and urged a policy of increased selectivity by both government and universities. The initial budget from President Clinton during the spring of 1993 continued the USA's concern with technology policy and provided modest increases for basic science throughout the federal agencies. Table 6 shows the budget proposals for research presented by each agency.

TABLE 6
US GOVERNMENT'S FUNDING FOR BASIC RESEARCH BY FEDERAL AGENCIES AND FOR UNIVERSITIES, SPRING 1993 (US$, billions)

	1992	1993	1994 (proposed)
Total basic research	12.9	13.5	13.9
National Institutes of Health (NIH)	5.5	5.7	5.8
National Science Foundation (NSF)	1.7	1.7	2.0
Department of Defense (DOD)	1.1	1.3	1.2
Department of Energy (DOE)	1.7	1.7	1.7
National Aeronautics and Space Administration (NASA)	1.8	1.9	2.0
US Department of Agriculture (USDA)	0.6	0.6	0.6
Other	0.5	0.6	0.6
Total R&D in universities	10.9	11.0	11.2

Sources: AAAS (April 1993) plus NSF, OSTP.

A tendency to focus on science policy, and especially the federal concern for university-based research, which dominated American thinking for much of the post-Second World War era – leaving technology policy to industry – has not disappeared. Yet there is a critical re-evaluation of the broader ensemble of basic science, together with applied science, and the diverse lines of technological development, application and manufacturing – all in a national economic context. In assessing this ensemble, one explicit criterion for investments is how to enhance economic competitiveness.

Accordingly, many of the already financially stretched universities have been compelled to make substantial retrenchments of ongoing research; and investigators have found increasing difficulty in maintaining their support for staff, equipment and supplies. Links with industry and state government are growing, partly to obtain the funds for maintaining research and partly to transfer research results to foster economic growth. Chronic frustrations are also deepening in the USA about how to finance the modernization of academic facilities, including the construction of laboratories. A similar situation in Canada also encompasses the strong insistence by the provinces of their constitutional role in education.

Regional funding trends

Limited data are available on the overall academic funding trends for the three countries. Information shown in Table 7 underlines the many indications that Mexico lags behind Canada and the USA in building both its universities and its R&D base. Some data from Canada are available, and occasionally in comparison with the USA, and these data are given in the lower half of Table 7.

For the USA, the proportion of the federal government's support for all R&D at universities has been declining – from about two-thirds a decade ago to 57% in 1992 – while support has been increasing from industry, private philanthropy, the state governments and the universities' independent funds. Industry's funding for universities rose 89% in real terms between 1985 and 1992, and accounted for 7% (US$1.4 billion) of US universities' 1992 R&D total. Given the economic constraints on the public sector throughout North America, this trend of growing industrial funding to campuses and separate research centres could well be repeated over the coming years in both Canada and Mexico. However, industrial support will probably remain a small fraction of total academic funding. Most observers agree that only governments can provide the crucial support for the most basic science and for core assistance to doctorate-granting institutions.

TABLE 7
ACADEMIC EXPENDITURE ON R&D, 1987
(constant 1980 US$, billions)

	Expenditure	% national R&D	% GDP
Mexico	0.1	20	0.06
Canada	1.4	23	0.32
USA[1]	18.5	14	0.41

Higher education expenditure on R&D (current PPP$[2])

	1986	1991
Canada	1.4	1.9
USA[1]	16.6	25.3

1. Includes federally funded R&D centres, i.e. special units affiliated with or administered by universities.
2. Purchasing power parity.

Sources: CONACYT, 1992, based on OECD Observer No. 164, 1990 and OECD, 1992.

Merit reviews and other criteria

In the USA, funding for much university research has been primarily based on a competitive proposal and review system rather than on general institutional support. This classical American pattern of national competition in each field among individual academic investigators has been sustained. But the process of merit review (or 'peer review') has been under scrutiny for a variety of reasons. One cause of disappointment is simply that – given the large pool of scientists and scarce funding – only about one in four or five grant applications from competent investigators is receiving support. Thus there is understandable anxiety about whether fine distinctions can be drawn between the best and nearly best applications.

Furthermore, in the light of the enormous demand for spreading research skills and modernizing research facilities, political arguments have frequently been made about the need to make grants to certain regions or institutions that have not received substantial funding in the past. These pressures for equitable geographical distribution of research activity are seen in each of the three countries in North America. In the USA, circumventing merit review in order to allocate funds to a particular region or institution (called 'earmarking') has grown to well over US$1 billion a year, and has become bitterly controversial. In the Canadian provinces as well as in Mexico (especially outside Mexico City) there are comparable efforts to distribute scientific and engineering competence.

Capacity building

The term 'capacity building' usually characterizes the goals in developing countries to build the capabilities for conducting research and to spread technical literacy across the entire population. Yet the term may also be applied to developed countries.

In the USA and Canada, for example, greater efforts are being devoted to reform K-12 (kindergarten to Grade 12, i.e. first- and second-level) education in science and mathematics. The drive comes from not only the comparatively poor performance of American children in international evaluations, but also the need for a much more highly skilled workforce to compete economically in the 21st century. In Mexico, the term 'capacity building', used in its traditional sense, means re-energizing a commitment to S&T as the national economy aims to flourish in worldwide markets.

In short, throughout North America, in both developed and developing parts of society, both the public and private sectors are thinking more frequently in terms of nurturing the long-range capacity of the S&T base.

INTERNATIONALIZING SCIENCE AND TECHNOLOGY

Science and technology are among the most international of human activities. This has been true for hundreds of years, as ideas have crossed borders with impunity. But with interconnected computers, telephones and fax machines in virtually every university and research laboratory, international contacts are almost instantaneous. Now, more than ever before, scientists and engineers are as likely to work with colleagues across the border as they are with those down the corridor in their own laboratory. The same is true for education in science and engineering. Students at all levels, but especially at the doctoral and postdoctoral stages, seek out institutions irrespective of national borders. Universities in the USA, and to a lesser extent Canada, have benefited from this flow. In 1991, there were over 100 000 non-US citizens enrolled in graduate studies in science, engineering and health fields in US colleges and universities. They represented 28% of all graduate science students and 47% of all graduate engineering students.

Striving for excellence

Global cooperation in S&T takes place in a climate of intense competition: in industrial technology, in basic research and in education. Increasingly, the driving force is the imperative for excellence in order to gain or maintain a position of leadership in a highly competitive field.

The application of this principle of seeking excellence is seen vividly in the R&D, services and educational areas. In R&D, alliances between leading multinational high-technology corporations based in different countries no longer elicit substantial attention from the press. Engineering services are now procured routinely in foreign countries by American and Canadian companies. And the US annual flow from educational services (mostly foreign undergraduate and graduate university enrolments) is now US$5 billion per year, a sizeable portion of this representing science and engineering. In certain burgeoning fields – ranging from environmental science to telecommunications – university and industry groups are likely to form more *ad hoc* coalitions as both investments and scientific personnel grow rapidly.

Canadian-US-Mexican cooperation

Informal cooperation between Mexican, Canadian and US researchers has been active and increasing for years. Most of this cooperation is not officially documented, but is readily apparent on university campuses and in corporate laboratories. Professional associations, such as the American and Mexican physical science and engineering societies, are also becoming involved.

Widely active US-Canadian cooperation in S&T at the governmental level involves dozens of US agencies and their Canadian counterparts. As is usual, joint projects range from basic science through space, health, agriculture and energy research, to mention a few of the more important areas. Of special interest is US-Canadian cooperation in both conducting and planning several Big Science and technology projects. These include the space station, the KAON accelerator in nuclear physics planned for British Columbia, the superconducting super collider under construction in Texas, and a pair of 8-metre telescopes planned in collaboration with the UK.

The Mexico-US bilateral Science and Technology Agreement provides an important framework for cooperation, with ongoing programmes under about 30 memoranda of understanding between Mexican and American agencies. Areas of strong emphasis include science and engineering education, materials and biotechnology. Genetic engineering of drought-resistant crops is high on the current agenda of cooperation. The creation and funding of an independent binational foundation in 1992 to support US-Mexican collaborative research augurs well for the continued growth of this relationship.

Both Mexican and Canadian universities are now linked to the US supercomputing network; linking additional academic institutions is a priority for all three countries. In the future, the North American Free Trade Agreement (NAFTA) would accelerate the process of integrating science and technology among the three countries that is already well underway.

Megascience cooperation

Today the costs of many current and proposed Big Science ('megascience') projects exceed the funding ability of any one country, no matter how large. This is true for both single facility (e.g. particle accelerator) and distributed (e.g. global change research programme) efforts. Both types of megascience projects are characterized by very large data management requirements and even bigger budgets.

Recognizing the need for greater international cooperation in megascience projects, the USA and Canada pioneered efforts to establish a 'Megascience Forum' within the OECD. The March 1992 meeting of the OECD science and technology ministers approved such a Forum as its first priority. Meeting for the first time in July 1992, the OECD Megascience Forum serves both an analytical and a communications function. While not intended to provide a framework for allocating resources or for making the hard political decisions required for a more extensive internationalization of Big Science, the Forum should fulfil the critical function of sharing information on plans for Big Science endeavours.

POLICIES FOR SCIENCE AND TECHNOLOGY

Policies for science and technology are both explicit and imputed from policies in other areas or from budget decisions. There is an ongoing debate as to whether S&T (R&D) budgets lead or lag behind explicit science and technology policies.

The USA

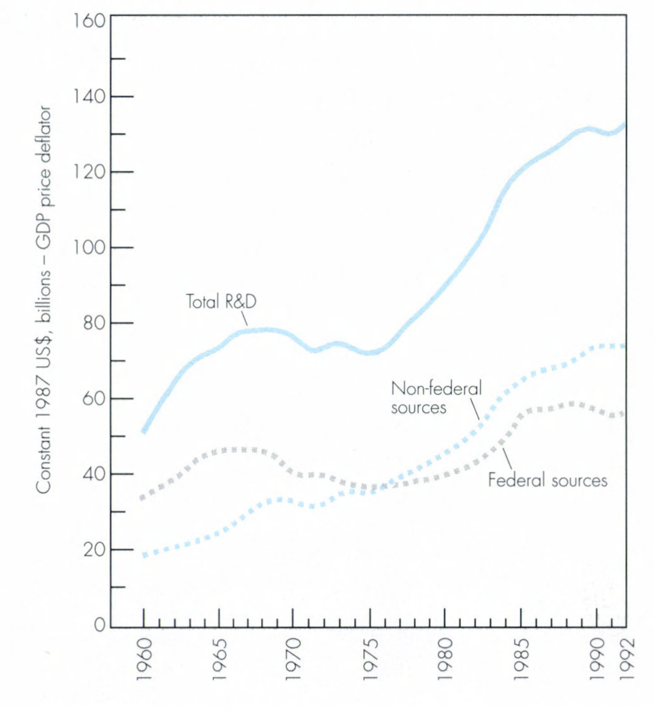
In the USA, S&T budgets are often a leading indicator of policies. For the period since the Second World War, US science and technology policy is illuminated by an examination of R&D budget trends.

In the private sector, R&D funding tripled in real terms from 1960 to 1990, totalling US$89 billion by 1992. Over 90% of this is company funded. This steady increase reflects a conviction by company managers that increased investment in R&D is required for success in the global marketplace for high-technology products and services. Running faster is necessary just to keep up in high technology. The slight (inflation-adjusted) decrease in company-funded R&D in 1990 and 1991, and a projected 1992 increase barely ahead of inflation, are disturbing. It is too early to tell whether this is or is not a temporary fluctuation.

US government funding of total R&D since 1960 has been less consistent, with the four distinct periods shown in Figure 4. From 1960 to 1968 there was robust growth, reflecting the race to deploy intercontinental ballistic missiles and to go to the Moon. The period 1968-75 saw a substantial real decrease, while the strong growth spurt from 1975 to 1985 reflected mainly the military technology build-up during the Reagan years as well as the growth of life sciences. Since 1985 government funding of R&D has kept up with inflation, but not much more.

The story for basic research, overwhelmingly government-funded, is more consistent. With the exception of the post-Apollo period 1968-75, when there was a slight inflation-adjusted decrease in government support, basic research funding has experienced strong, steady growth. Much of this growth has occurred in the life sciences, expressed through the budgets of the National Institutes of Health.

FIGURE 4
US NATIONAL R&D FUNDING BY SOURCE



Source: NSF 92-330, October 1992.

The governmental policies imputed from these trends are: strong, steady support for basic research, reflecting a political consensus as to the wisdom of these investments, and swings in support for applied research and for development, reflecting changing policies external to S&T and based on concerns about national security, space exploration, and international economic competitiveness.

US technology policy

The most significant recent change in policy relates to technology, not science. President Clinton announced a Technology Initiative in February 1993 to focus American technology on three central goals: long-term economic growth that creates jobs and protects the environment; a more efficient and responsive government; and world leadership in basic science, mathematics and engineering. President Clinton's Science and Technology Advisor, John H. Gibbons, has much of the responsibility for the initiative's implementation.

The new Clinton thrust initiates a policy to promote technology as a catalyst for economic growth by increased direct government support for the development, commercialization and deployment of new technologies; improving the business climate for innovation with changes in the tax, trade, regulatory and procurement policies; investing more in education, 'life-long learning' and educational technology; accelerating the introduction of a high-speed communications infrastructure ('information superhighways'); upgrading the transportation infrastructure; and improving governmental effectiveness in areas such as information technology.

In contrast, the Bush Administration's Technology Policy, issued in September 1990, identified a less activist role for government. It emphasized the principal role of the private sector in identifying and utilizing technologies for commercial products and processes, and emphasized that government policies can help establish a favourable policy environment, but cannot be a substitute for aggressive private sector action.

The Clinton Administration has announced substantial budget increases for support of civilian technology for the fiscal years 1994 to 1997. The increases are in the context of an Administration commitment to shift the ratio of military to civilian R&D spending from 60:40 to 50:50 within five years. Given the stringent budget constraints faced by the US Government, growth in overall R&D support beyond inflationary adjustments is unlikely.

Mexican technology policy

The level of support for science and technology in Mexico, as described earlier, is small by US standards. It currently spends about 0.4% of its GDP on S&T, compared with 2.8% in the USA and 1.4% in Canada. The 0.4% is about the same as it was in 1980, but represents a substantial recovery from the depressed levels following the oil price plunge in the early 1980s. The vast majority (84%) of

R&D funding in Mexico comes from the federal government.

Like many other countries, Mexico is concentrating on a number of critical technologies, notably biotechnology. It is emphasizing the development of new technologies for economic growth. Most new technology is coming from foreign sources. However, a recent survey shows the share supported by private industry is increasing rapidly, reaching 22% in 1992. Mexico is also taking steps to participate in the major international research efforts, such as the superconducting super collider and the projects in global change and human genome research.

The federal government is investing in human resources, and the number of scientists and engineers is growing. The Mexican National Council for Science and Technology (CONACYT) is showing renewed vitality, with more than a doubling of its budget since 1989. It has also recognized the need to monitor and track its investments by developing a system of 'science indicators', and the USA is cooperating with Mexico in this effort, as are the OECD and UNESCO.

Canadian technology policy

Canada's R&D expenditure is about 5% of the US level, with government and industry expenditure approximately equal. This healthy ratio of private sector to government expenditure is unusual for a relatively small country, because of the tendency for R&D to be carried out in multinational companies' home countries. Energetic Canadian government intervention is in large part responsible for strengthening industrial R&D. Canada has a generous R&D tax credit, and preliminary 1993 data show increased corporate R&D spending even with slow overall economic growth.

The Canadian 'Prosperity Initiative' aims to develop a national consensus on programmes directed at the high-skill global marketplace. One key outcome of a year-long study of factors affecting competitiveness, completed in late 1992, *Inventing Our Future*, was to recognize the need to strengthen the S&T infrastructure, capabilities and skills of Canadians.

During 1992 the Science Council of Canada was abolished, and government laboratories experimented with ways to become more responsive to commercial market forces. The static government R&D budget was directed more toward scientific and technological infrastructure, health and civil space. For some time Canada has had substantial governmental intervention in industrial policy – more so than the USA – and the recent creation of the Department of Industry and Science shows continuing high-level adaptation.

Science and technology advisory mechanisms

This section is mainly about policies for science and technology. But providing reliable and timely advice about S&T in broader policy development (S&T for policy) is also important. Effective advisory mechanisms for both purposes are in place in all three countries at the highest level of government.

In Mexico, the President of the Republic has both a Science Advisor and a Science Advisory Council (Consejo Consultivo de Ciencias (CCC)). The CCC is composed of prominent scientists and engineers from a variety of sectors and disciplines. CONACYT and its Director also play a major role in policy development.

In the USA, a Science Advisor and a President's Science Advisory Committee (PSAC) were appointed in 1958, in the wake of the launch of Sputnik by the USSR. PSAC was abolished in 1973, and a White House Science Council advised the Science Advisor from 1981 until 1989. A President's Council of Advisors on Science and Technology (PCAST) was established by Executive Order in 1990, with its members consisting of prominent scientists and engineers. Chaired by D. Allan Bromley, the Director of the Office of Science and Technology Policy under President Bush, PCAST met regularly with the President and issued a number of reports on important policy topics. The National Science Board sets policy for the National Science Foundation and also influences broad US policy development in science and technology.

Canada's National Advisory Board on Science and Technology (NABST) was formed in 1987 with the mandate to advise the Prime Minister on how S&T could be more effectively utilized in Canada. Chaired by the Prime Minister, its members are from government, business, labour and education communities in Canada.

NAFTA

With the North American Free Trade Agreement (NAFTA) on the horizon, changes in the scientific and technological relationships between Canada, Mexico and the USA will be accelerated. On the agenda are issues such as intellectual property rights, industrial R&D, and cooperation in academic research programmes. The dominant role of the USA in S&T causes unease among the technical community in Mexico, but also provides increased opportunities for participation in unique research efforts.

At the official level, Joint Consultative Groups have been established between the USA and Mexico and between the USA and Canada. This mechanism provides opportunities for informal exchange between senior officials on a wide variety of issues, and for the identification, discussion and catalysis of collaborative activities. The US PCAST and Canadian NABST advisory panels have also held joint meetings, and the Mexican CCC co-sponsored a major International Seminar on Science and Technology and the Free Trade Agreement in 1991.

CONCLUDING NOTE

Throughout the North American region, scientific, engineering and health research is vigorous despite the financial constraints. The enterprise is thoroughly international – and growing more global every day – and at the same time well integrated with evolving expectations of how science and technology should contribute to national goals that are themselves changing. Shaping an optimum mixture of private competition, public support and international cooperation is central to debates on the roles of science and technology in North America over the next few years.

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RODNEY W. NICHOLS is Chief Executive Officer of the 176-year old New York Academy of Sciences. Previously he was successively Vice-President and Executive Vice-President of the Rockefeller University and Scholar-in-Residence at the Carnegie Corporation of New York.

A graduate of Harvard University, Mr Nichols has served as an applied physicist, systems analyst and an R&D manager in both private industry and in government. He has advised the White House Office of Science and Technology Policy, the State, Defense and Energy Departments, the National Institutes of Health, the National Science Foundation and the United Nations. He has represented the USA in international negotiations on arms control, at conferences on technology transfer and was Vice-Chair to former President Jimmy Carter for the Carnegie Commission's December 1992 report on *Partnerships for Global Development*. Mr Nichols was awarded the Secretary of Defense Medal for Distinguished and Meritorious Civilian Service. Among his present interests is international collaboration in fields such as energy, health and the basic sciences.

J. THOMAS RATCHFORD is Professor of International Science and Technology Policy at George Mason University, where his teaching and research involve a variety of science and technology policy issues, especially the interface between trade and technology.

Educated and trained as a solid-state physicist, Dr Ratchford was a faculty member at Washington and Lee University and served on the research staffs of various private and governmental laboratories. He was subsequently responsible for formulating and administering a basic research programme for the Air Force Office of Scientific Research before becoming a member of the professional staff of the US Congress.

Later, Dr Ratchford was to serve as the Associate Executive Officer of the American Association for the Advancement of Science (AAAS) where he was deputy to the Chief Executive Officer and headed the Association's three programme directorates of Education and Human Resources, International Programmes and Science and Policy Programmes.

Before his recent move to George Mason University he was Associate Director for Policy and International Affairs at the White House Office of Science and Technology Policy.

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LATIN AMERICA

Raimundo Villegas and Guillermo Cardoza

In most Latin American countries, science was at its beginnings or at best an uncertain human activity less than 50 years ago at the end of the Second World War. This situation has undoubtedly changed in many cases thanks to national efforts and to international cooperation. However, it is unfortunate that having reached such higher levels these countries have remained in a steady state or, at best, barely managed to maintain a minimum rate of growth. The indications are that, in order to attain levels of scientific progress high enough to have an impact on integral development, very profound policy changes are required in Latin American countries.

In most of the less developed countries, scientific research and related activities are marginal, with limited impact on society and on the process of development. By contrast, in developed countries science is an essential component of education and culture, in addition to its being closely linked, through its application, to the remaining social systems, including the economic one.

The aim of this chapter is to present an account of the evolution and present state of science in Latin America; it will conclude with a critical vision of the factors that appear to limit scientific progress, and some ideas as to how they could be overcome.

When we refer to science, it is in the broad sense of the word, including research and the many activities depending on it. We consider research (from basic and basic-oriented to research and development (R&D) and technological innovation) the essential component of science. This recognition attempts to underline that it is the new scientific knowledge obtained through research that we teach, disseminate, apply and question until it is transformed once again into a research topic.

THE LATIN AMERICAN AND CARIBBEAN COUNTRIES

The so-called Third World occupies two-thirds of the Earth's surface, and a quarter of this corresponds to Latin America and the Caribbean. The Third World concentrates 78% of the world's population, 10% being found in the Latin American and Caribbean region (World Bank, 1991). The different regions of the Third World are quite heterogeneous from the political, economic and social standpoints and this heterogeneity is also evident between the countries which make up each of these regions.

The Latin American and the Caribbean region is made up of 27 countries, has an area of over 20 million square kilometres and a population of 421 million inhabitants, figures similar to those of Canada and the USA combined (World Bank, 1991). Although an overview of the region suggests some degree of homogeneity, current levels of achievement vary from one country to another when considered in absolute terms.

Latin America

There are 19 Spanish- and Portuguese-speaking countries considered traditionally as Latin America. The Latin American countries are distributed from north to south in the following sub-regions: Mexico; Central America (Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama); the Spanish-speaking Caribbean (Cuba and the Dominican Republic); the Andean sub-region (Bolivia, Colombia, Ecuador, Peru and Venezuela); Brazil; and the South Cone (Argentina, Chile, Paraguay and Uruguay). Central America and the Spanish-speaking Caribbean are sometimes considered a single Latin American sub-region. On the other hand, Haiti, a Francophone Caribbean island, is considered part of the Caribbean.

Whilst these countries share a common history, culture, religion and language (Spanish and Portuguese are similar languages), homogeneity seems to be rather more valid at sub-regional level, notwithstanding that in sub-regions formed by three or more countries at least one is significantly different from the average.

The Caribbean

Caribbean countries are conventionally considered as those located on the islands of the Caribbean Sea. They are generally grouped according to language, namely: Anglophone countries (Bahamas, Barbados, Grenada, Jamaica and Trinidad and Tobago); Francophone (Haiti); and Spanish-speaking countries (Cuba and the Dominican Republic). It is interesting to note that some of the continental countries bordering the Caribbean Sea, such as Mexico, Central America, Colombia and Venezuela, consider themselves part of the Caribbean continental America, which also includes English-speaking Guyana, and Dutch-speaking Suriname. History and language have traditionally led to an association of these last two countries with the Caribbean, although they are situated on the Atlantic coast.

THE EVOLUTION OF SCIENCE IN LATIN AMERICA

Pre-Columbus to the end of the 19th century

Before the arrival of Christopher Columbus in Latin America, the Aztec, Mayan and Incan civilizations had attained appreciable levels of development in certain areas of knowledge, such as mathematics, astronomy, agriculture and medicine – empirical and speculative knowledge which these aborigines were able to communicate both orally and in written form (Sagasti, 1978). Nevertheless, Western scientific creation, i.e. science as it is known today in developed Western countries, reached the region many years after Columbus and the Spanish and Portuguese *conquistadores*, among other reasons because science was only just beginning in Europe at the end of the 15th century.

Columbus first landed in La Española in the Caribbean Sea (an island which today is made up of the Dominican Republic and Haiti) in 1492, and in Tierra de Gracia (today Venezuela) on the American mainland in 1498. Scientific institutionalization, on the other hand, was to begin in Europe with the creation of the scientific academies more than a century later (*Accademia dei Lincei*, Rome 1603; *Accademia del Cimento*, Florence, 1657; Royal Society, London, 1660; *Académie des Sciences*, Paris, 1666). Later events which involved Spain as well as Portugal from the last third of the 16th century to the end of the 18th century, included the counter-reformation, the elimination of the Spanish-Jewish community and the colonization of Latin America (Lopez-Piñero, 1969). The consequences of these were, on the one hand, the intellectual isolation of Spain and its colonies – to the point that during the reign of Philip 11 Spaniards were forbidden to study and to teach in foreign countries – and on the other, the fact that pure science was abandoned in order to concentrate on practical matters and applied knowledge. Paradoxically, this obsession with practical matters was not accompanied by an appreciation of manual work (Sagasti, 1978), so necessary for the progress of experimental science and of human work in general. These events prevented Spain from participating in the emergence of modern science as it occurred in Europe during the 17th century.

An appreciable but transient scientific renaissance occurred in Spain during the reign of Charles III. This was the time of the Spanish Enlightenment and from there, mostly through the universities, the philosophical ideas fashionable in Europe reached colonial Latin America, together with a new scientific perspective for the teaching of medicine, botany and physical sciences (Steger, 1974). Although scientific creation was never an important human activity during the formative process of Latin America, there were certain activities of applied science, such as expeditions to study nature plus certain attempts to adapt plants and animals of European origin (Roche, 1976).

The 18th century also marked the end of the so-called colonial period for most Latin American countries. The era of political independence began during the first part of the 19th century, followed by a long period in which efforts were made to consolidate autonomous national governments.

During the four centuries following the landing of Columbus – from the end of the 15th century until the end of the 19th century – Latin America witnessed the arrival or the emergence of naturalists, investigators and students of nature who initiated a growing interest in science. As examples we can mention, in the 16th century, Francisco Hernandez in Mexico and, in the 18th century and beginning of the 19th century, Charles Marie de la Condamine, Louis Godin and Pierre Bouguer in Ecuador, Hipólito Ruíz and José Antonio Pavón in territories belonging today to Chile and Peru, José Celestino Mutis, who headed the Botanical Expedition and was accompanied by Francisco José Caldas, Jorge Tadeo Lozano and Francisco Zea in Colombia, and Alexander von Humboldt who travelled through Venezuela, Colombia, Ecuador and Peru. Such studies were continued well into the 19th century by distinguished scientists like Agustin Codazzi in Venezuela, Francisco Javier Muñiz in Argentina and Charles Darwin who travelled from Brazil to Argentina, Chile, Peru and to the Galapagos Islands of Ecuador. Medical investigators like José Hopólito Unanue and Daniel A. Carrión worked in Peru, José María Vargas and Luis Daniel Beauperthuy in Venezuela and Carlos Finlay in Cuba. Some believe that these individuals constitute the source of scientific tradition in Latin America (Weinberg, 1978). Others look upon them as isolated cases. Whichever may be the fairest viewpoint, they and others like them form an important part of the scientific past of the region.

The start of professional scientific research

To those names mentioned above we could add others from the first half of the 20th century and from more recent years. For instance, we would mention Bernardo Houssay, Eduardo De Robertis and Luis Leloir in Argentina; Oswaldo Cruz and Carlos Chagas in Brazil; Eduardo Cruz-Coke in Chile; Arturo Rosenblueth in Mexico; Pio del Rio Hortega and Clemente Estable in Uruguay; Carlos Monge in Peru and Augusto Pi-Suñer and Francisco De Venanzi in Venezuela. It is interesting to note that all these men carried out research in the medical or biological sciences. Most were born in Latin America, some were sons of immigrants and two were born in Spain. It fell to them and many others like them to initiate the formalization of scientific research in the various countries of Latin America, as well as its teaching and its practice as a profession, with norms for admission, practice and permanence in its realm.

The European link with Latin America is not unexpected, but nevertheless it is noteworthy that during the present century the flowering of different sub-regions and countries of Latin America seems to have heen directly linked with migratory flows from different European countries. Thus, the rather earlier scientific development of the South Cone sub-region, particularly Argentina, Chile and Uruguay, appears to have been the result of the immigration of specific European scientists. Similarly, the more recent scientific development of Mexico and Venezuela can be related to the arrival of individual scientists from Spain and other European countries.

Nevertheless, for science to flourish, other conditions are needed; for instance, the existence of individuals, researchers and students who could act as hosts to these immigrant scientists. In addition, there needs to be a sufficient level of economic well-being to have the resources to acquire the necessary equipment and materials. Such conditions are usually to be found in universities or research centres. The next step involved the training of national human resources. Almost all these groups were started by university students who continued their formal graduate education abroad or received advanced training, usually outside the region.

The first impact of the establishment of scientific research groups in certain university schools and departments in several Latin American countries was the improvement in the quality of teaching and practice of related professions, i.e. medicine, agronomy, veterinary medicine and engineering. Later, science faculties were established, along with research institutions, where basic science and certain aspects of applied science continued their development.

It is interesting to note that pure and applied biology (i.e. medical, agricultural and environmental sciences) was always at the origin of research activities in the various countries of Latin America. This was usually followed by research in engineering, starting with those aspects more closely linked to human life (i.e. housing and sanitary engineering) up to sophisticated areas related to basic sciences (chemistry, physics and mathematics) and to industrial development (i.e. chemical, mechanical and electronic engineering).

By the end of the first half of this century, most Latin American countries (but unfortunately not all) had reached a certain level of scientific development. There were university research units in schools and research centres linked to the state and to public and community services, as well as certain research and development units linked to industry.

In some countries, national academies already existed, usually called national academies of exact, physical and natural sciences, created and funded by the state, with a limited number of lifetime members (approximately 30 or 40).

Open scientific societies, or societies initiated by friends of science of a private character, already existed or were in the process of being created in the different countries. Among them, those known as societies for the advancement of science played a very important role in science promotion. In many countries, these societies served as teaching centres of certain basic norms for the practice of science.

The formalization of science

Shortly after the end of the Second World War, we witnessed the emergence of the United Nations (UN) and of its specialized agency involved with science: the United Nations Educational, Scientific and Cultural Organization (UNESCO). One of the first goals of UNESCO was to promote and facilitate the development of science in less developed countries, through the study of the scientific situation of these countries followed by the proposal of specific policies and actions.

National research councils: One of the most important events in Latin America during the second half of this century, and one that was to make a significant contribution to the progress of science, was the creation of national councils for the promotion and support of scientific activities. These councils were composed of representatives from the government, public and private research organizations, universities, industries, scientists and users of know-how and knowledge (Comisión Preparatoria, 1965; Roche, 1992), and their design was contributed to by UNESCO (Behrman, 1979). They were generally called national scientific and technological research councils and for the most part were associated with organizations very close to the head of state, usually decentralized (that is, separate from central administration) to emphasize their autonomy and technical nature. They were also allocated funds for financing scientific research and educational projects. One of the most recent successful programmes of the councils is the Researcher's Career (or Researcher Promotion Programme) which functions as a mechanism to promote recognition and at the same time help strengthen researchers' roots in their own country.

Although the results of this process reflect a certain level of institutionalization of scientific activities of the region, we cannot say that science has reached an acceptable level of 'social legitimacy'. In fact, scientific activities are still marginal phenomena, and the Latin American countries must continue efforts to consolidate a genuine scientific culture, and create an awareness of the role of science in development by people at large.

Regional centres and networks: Another important action of UNESCO in the region was the promotion of scientific integration by the creation, together with the governments of several countries, of regional centres devoted to bringing scientists together through the organizing of symposia, workshops and training courses. Examples are the Latin American Centre for Physics (CLAF), the Latin American Biology Centre (CLAB), the International Centre for Tropical Ecology (CIET) and the Simon Bolivar International Centre for Scientific Cooperation (CICCSB). The first is situated in Brazil, the others in Venezuela.

The Latin American Biosciences Network (RELAB), part of the International Biosciences Network (IBN) and created by UNESCO, the International Council of Scientific Unions (ICSU) and the Organization of American States (OAS) with the support of the United Nations Development Programme (UNDP), was established less than two decades ago. This scientific network allowed the establishment of links between many researchers, and promotes the organization of binational and multinational research programmes. More recently, the Latin American Biotechnology Network was created along similar lines, under the sponsorship of UNDP, UNESCO and the United Nations Industrial Development Organization (UNIDO).

Research centres of an international character have also been created to promote interest in areas of great importance to the region, such as agriculture. Examples are the International Centre of Tropical Agriculture (CIAT) in Colombia, the International Potato Centre (CIP) in Peru, the Central American Institute of Industrial Research and Technology (ICAITI) in Guatemala, and the Inter-American Institute of Agricultural Sciences (IICA) in Costa Rica.

Regional S&T programmes: Besides these scientific centres, science and technology programmes were established in different regional and sub-regional organizations. Two decades ago, the OAS programme proved very important as it served as liaison for North-South cooperation between the USA and the Latin American countries.

An example of a sub-regional programme is provided by the Andres Bello Agreement (SECAB) of the Andean countries, which has its secretariat in Colombia. This Agreement has, among its mandates, that of promoting sub-regional scientific development and integration. Given the importance of science in the improvement of education, and the quality of life, and the modernization of the Andean sub-regional countries, this programme is expected to have a very important role in the future.

At present, the Bolivar Programme, a regional arrangement sponsored by Venezuela with the support of the Inter-American Development Bank (IDB), is geared to linking research centres with industries in different countries of the region.

Ministries, secretariats and offices for science and technology: The existence of S&T programmes linked to the different sectors of the state in several countries during the last few years, has led to the creation of ministries, secretariats and offices at a government level responsible for overseeing the incipient S&T, and attempting, in certain cases, to carry out horizontal planning and coordination, over and above the links and attachment that research or R&D institutions have with a given sector, be it education, health, agriculture, environment, natural resources or energy. These ministries, secretariats and offices have sometimes functioned efficiently as promotion and liaison entities.

Non-governmental organizations (NGOs): These organizations have recently assumed an important role in the promotion of science and research-linked tasks in the countries of the region. NGOs have had a significant part to play in research activities in several Latin American countries.

The Latin American Academy of Sciences: Ten years ago, a group of scientists created the Latin American Academy of Sciences (ACAL) with the purpose of promoting the development of science and the integration of Latin America. ACAL is a non-governmental, private organization. New members are elected by existing members on the basis of scientific achievement, without any type of discrimination. The Academy has a regional cooperation programme and its main activities involve information and scientific exchange, as well as cooperation with the regional centres and the promotion of different networks. The ACAL Regional Programme is a joint enterprise of the Simon Bolivar Foundation for ACAL (FSB-ACAL), ICSU-COSTED, UNESCO and the Third World Academy of Sciences (TWAS).

SCIENCE IN LATIN AMERICA: THE PRESENT SITUATION

In this section, we will summarize the present situation of science in Latin America based on information contained in the databases of ACAL, compiled directly by the Academy itself (Cardoza and Azuaje, 1992; Villegas and Cardoza, 1987, 1990 and 1991) or, in its absence, by the sources indicated in the footnotes to tables and figures. In general, the results have been broken down by sub-regions and by each of the 10 countries producing the largest number of scientific publications during 1991.

Table 1 offers data on human resources, expenditure and scientific publications for each country and sub-region in Latin America. These data were used to calculate the values contained in most of the figures in this article. Discussion on the possible significance of observations takes into account population, levels of education, and economic well-being of each country and sub-region.

Human resources

Figures 1 and 2 show respectively the human resources devoted to research in the sub-regions and in each of the 10 countries of Latin America producing the largest number of scientific publications during 1991 (Table 1). The total number of researchers and associates from the 19 Spanish- and Portuguese-speaking countries of Latin America registered in the ACAL database is 142 904.

Figure 1 shows that the Brazil, South Cone and Caribbean sub-regions have more than 400 individuals devoted to research per million inhabitants, whereas in the Mexico, the Andean and Central American sub-regions there are close to 200 individuals per million inhabitants. As seen in Figure 2, it is also possible to group the countries into two: the first group made up of Brazil, Argentina, Cuba, Costa Rica and Uruguay and the second of Mexico,

TABLE 1
SCIENCE IN LATIN AMERICA

Country/ sub-region	R&D personnel	Expenditure (1991)		Scientific publications		Cooperation[1] (1990)	
		US$ (millions)	% GDP	Total (1991)	Per million inhabitants	Regional	International
Mexico	**14 909 (1984)**	**961.0**	**0.35 (1991)**	**1 608**	**19.3**	**63**	**774**
Costa Rica	1 453 (1989)	42.9	0.89 (1989)	108	38.5	10	102
El Salvador	142 (1989)			3	0.6	2	5
Guatemala	2 021 (1990)	12.3	0.10 (1990)	75	8.9	0	38
Honduras	703 (1990)	4.2	0.04 (1990)	18	3.9	2	65
Nicaragua	725 (1987)	10.0	0.37 (1985)	22	6.2	5	12
Panama	850 (1990)	20.7	0.41 (1990)	81	36.8	18	92
Central America	**5 894**	**90.1**		**307**		**37**	**314**
Cuba	12 052 (1989)	171.2	0.85 (1990)	155	15.3	10	95
Dominican Rep.	500 (1990)			25	3.7	10	29
Caribbean	**12 552**	**171.2**		**180**		**20**	**124**
Bolivia	890 (1986)			33	4.9	9	41
Colombia	4 449 (1990)	68.8	2.20 (1987)	196	6.5	98	201
Ecuador	760 (1984)	11.4	0.11 (1989)	61	6.1	7	46
Peru	4 858 (1981)	106.1	0.23 (1987)	176	8.5	18	156
Venezuela	5 457 (1990)	200.0	0.45 (1990)	494	27.1	61	215
Andean	**16 594**	**386.3**		**960**		**193**	**659**
Brazil	**65 000 (1990)**	**3 179.0**	**0.89 (1990)**	**3 735**	**26.4**	**148**	**1 424**
Argentina	19 000 (1988)	466.0	0.80 (1992)	1 934	62.1	117	644
Chile	4 009 (1987)	90.6	0.46 (1988)	1 151	92.0	90	566
Paraguay	807 (1981)	1.5	0.03 (1990)	38	9.5	1	4
Uruguay	2 093 (1990)	18.0	0.20 (1987)	96	32.0	15	36
South Cone	**25 909**	**576.1**		**3 219**		**223**	**1 250**

1. Joint authorship of scientific publications.

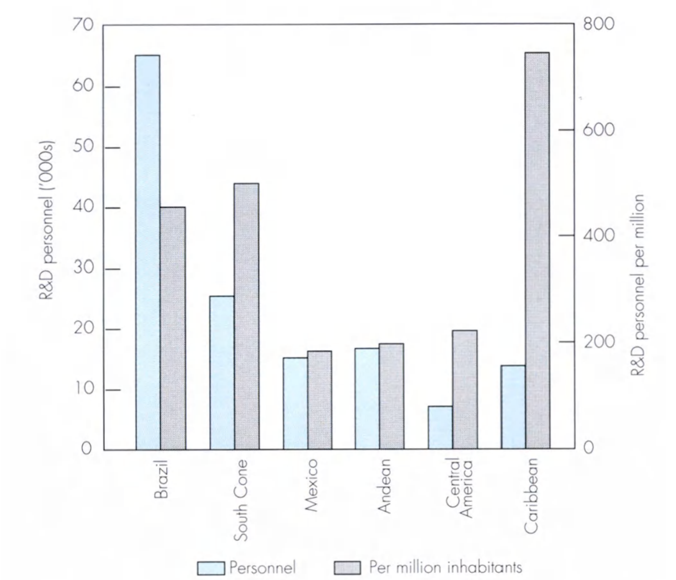
Source: Latin American Academy of Sciences (ACAL).

Chile, Venezuela, Colombia and Peru. Although these data were supplied to the ACAL database by each country in response to a standard questionnaire, it is difficult to dismiss altogether interpretational differences of certain definitions like researcher, associate, technician and auxiliary, which might have influenced the data. Nevertheless, we consider that in spite of this, the results reveal the relatively major effort made by some countries such as Argentina, Cuba, Costa Rica and Uruguay in fostering scientific work.

Research centres

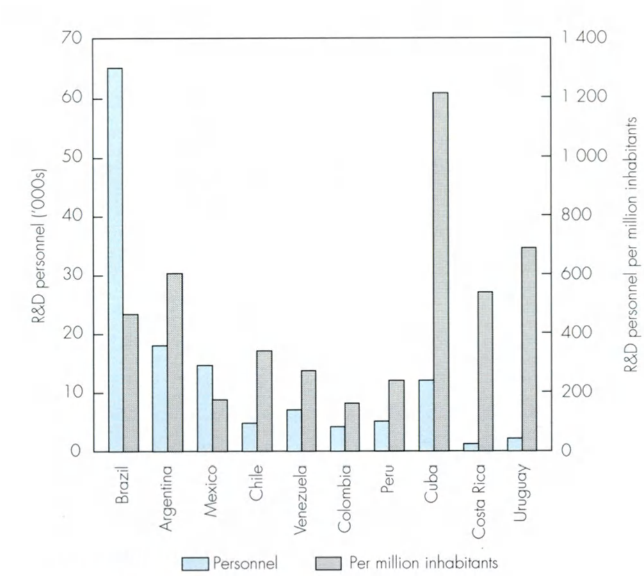
Figure 3 shows the breakdown by research field of the 2 280 research centres/units in the 19 Spanish- and Portuguese-speaking countries of Latin America registered in the ACAL database. As you will notice, 60.9% are

FIGURE 1
R&D PERSONNEL BY SUB-REGION, 1991



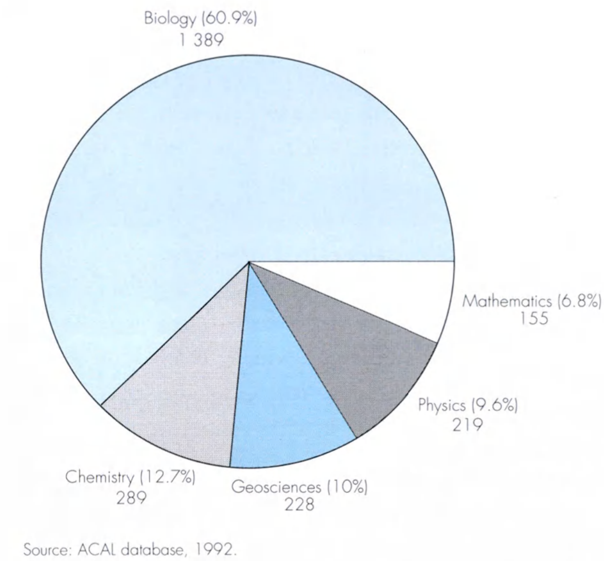
Source: ACAL database, 1992.

FIGURE 2
R&D PERSONNEL, 1991



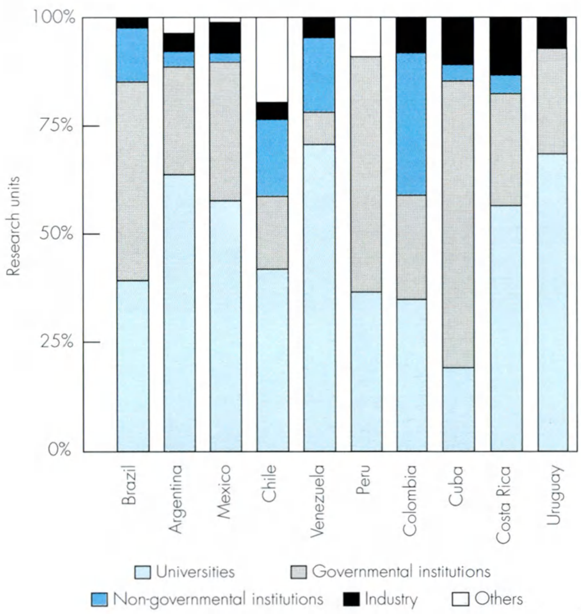
Source: ACAL database, 1992.

FIGURE 3
RESEARCH UNITS BY FIELD



Source: ACAL database, 1992.

FIGURE 4
DISTRIBUTION OF RESEARCH UNITS

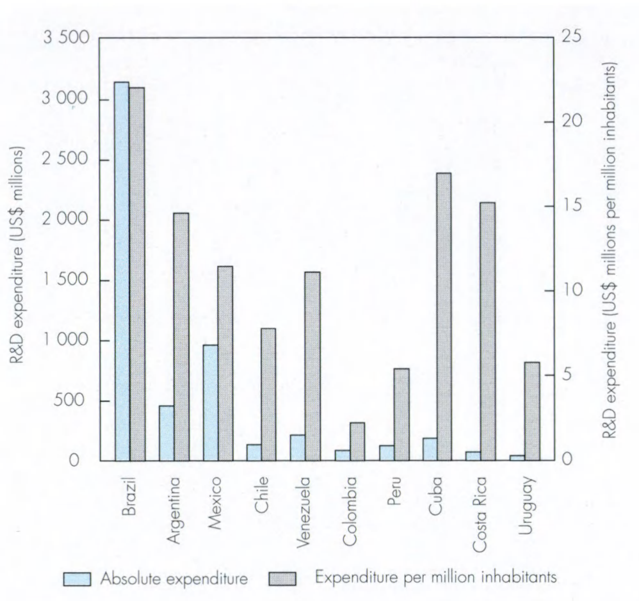


Source: ACAL database, 1992.

devoted to biology, including fields such as basic and applied medical sciences, agricultural and environmental sciences, and biotechnology. The remaining 39.1% are distributed in almost equal parts between chemistry, geosciences, physics and mathematics. This distribution reveals the importance given to biology in Latin America, such predominance being generally ascribed to the existence of important problems related to human health, nutrition and agriculture. More recently, activities associated with the preservation of the environment and the rational use of natural resources have also gained importance.

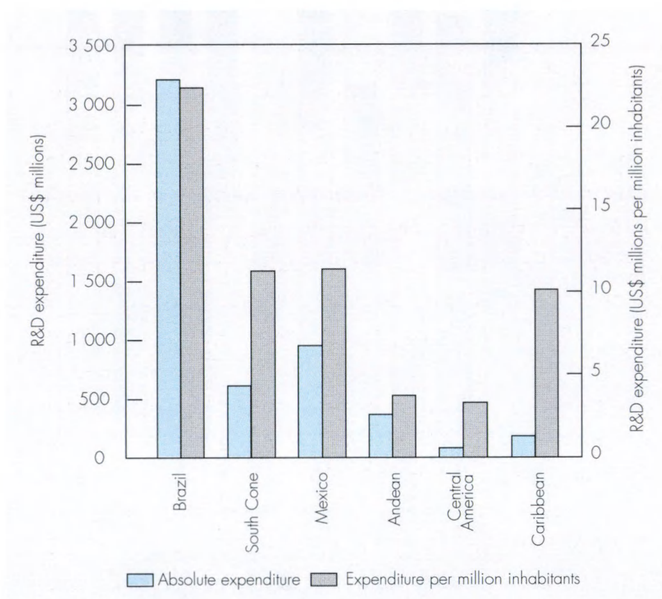
The links between research centres and universities, governmental and non-governmental research organizations and industry are represented in Figure 4 for the 10 countries selected according to the number of scientific publications during 1991. It is interesting to note that in Argentina, Mexico, Venezuela, Costa Rica and Uruguay, the highest percentage of research units operate within the framework of a university, whereas in Brazil, Peru and

FIGURE 6
R&D EXPENDITURE, 1991



Source: ACAL database, 1992.

FIGURE 5
EXPENDITURE BY SUB-REGION, 1991



Source: ACAL database, 1992.

Cuba, the highest percentage of institutions are linked with non-university governmental organizations. In Chile and Colombia, the research centres are equally distributed between universities and governmental and non-governmental organizations. It is worth noting that links with NGOs are quite significant in Brazil, Chile, Venezuela and Colombia; in the latter, 29.2% of research centres are associated with such organizations.

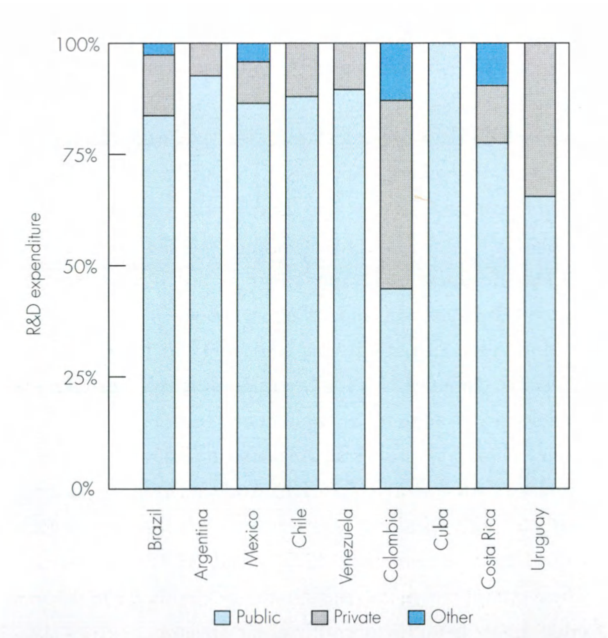
We would like to underline the relatively few links that exist between research centres and industry. In most of the 10 countries with the greatest scientific production, less than 10% of the research centres are located in the industrial sector, with the exception of Colombia, Costa Rica and Uruguay, with Costa Rica having the highest incidence (15.8%). One of the greatest challenges for science (in the widest sense) in the Latin American countries is the development and reinforcement of intramural research capacity in industry (Saldaña, 1992).

Expenditure

According to the IDB, the Latin American countries allocate annually 0.3-0.7% of their gross domestic product (GDP) to science, usually identified as R&D (GRADE, 1991). These percentages are undoubtedly important indicators of the interest and efforts each country has in science. It is important to stress that the way in which each country classifies its own research expenditure affects the calculation of the percentage of GDP dedicated to R&D.

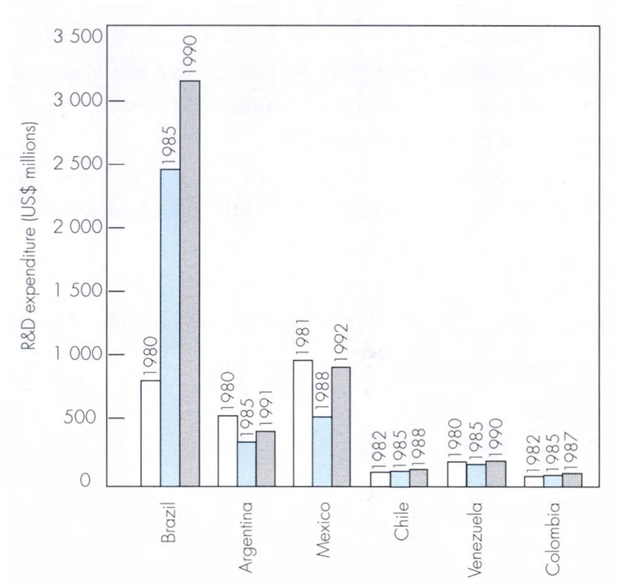
Estimated total Latin American expenditure in science was US$5 320 million in 1990. Net expenditure and expenditure per million inhabitants by sub-region and also by each of the 10 individual countries mentioned earlier, are shown in Figures 5 and 6 respectively. As seen in Figure 5, the estimated expenditure in the South Cone, Mexico and Caribbean sub-regions was close to US$10 million per million inhabitants, in Brazil it was slightly more than double that, and the opposite was true for the Andean and

FIGURE 7
R&D EXPENDITURE BY SOURCE, 1991



Source: ACAL database, 1992.

FIGURE 8
R&D EXPENDITURE OVER TIME



Source: ACAL database, 1992.

Caribbean sub-regions, with substantially less than US$5 million per million inhabitants.

We see from Figure 6 that, in addition to Brazil, Argentina, Mexico and Cuba, two countries in the Andean and Central American sub-regions, Venezuela and Costa Rica respectively, had expenditure of over US$10 million per million inhabitants, whereas two countries in the South Cone, Chile and Uruguay, spent between US$5 and 10 million. Only Colombia and Peru spent less than US$5 million per million inhabitants.

It is also interesting to note that, based on the data presented in Figure 7, more than 75% of the resources in eight of the 10 countries were of public origin. Only Colombia and Uruguay received more than 30% of their resources for science from the private sector.

Figure 8 illustrates the net expenditure spanning approximately a decade for the first six countries of the group of 10 selected according to their scientific production. What is evident here is the impact of the economic crisis in the early and middle 1980s which further depressed the region and was related to the commitments derived from the foreign debt acquired by countries in the hope of financing their development. Loans were offered and granted by financial organizations and banks of industrialized countries on very easy terms, with interest originally very low. Debt interest payments have deeply damaged the economies of Latin American countries and reduced the living conditions of most of the people in the area.

According to the data presented in Figure 8, Brazil was the only country which significantly increased scientific outlay during the decade. Mexico and Argentina reveal a decrease during the first half of the 1980s and a partial recovery during the second half. Chile, Venezuela and Colombia made efforts to maintain and even to slightly increase their expenditure during the same period.

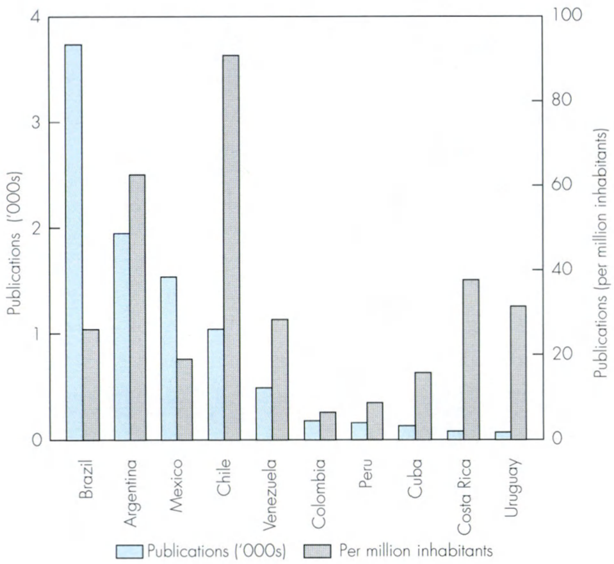
Scientific production

The indicator of scientific production used here is the number of scientific papers or articles in peer-reviewed journals with international circulation appearing in the *Science Citation Index* (ISI, 1980, 1985 and 1989-91*a*), from which data are calculated. *SCI* is considered the best indicator for scientific purposes. Scientific production per million inhabitants was also used to allow comparisons to be made.

The production of the various Latin American sub-regions during 1989 and 1991 is shown in Figure 9. The total numbers of publications were 8 517 in 1989 and 9 889 in 1991, about 1% of all annual scientific publications worldwide. Note that the publications from Brazil, the South Cone sub-region and Mexico represent 87.3% of the total in 1989 and 86.6% in 1991. The Andean, Central American and Spanish-speaking Caribbean sub-regions together contribute the remaining 12.7% and 13.4%, respectively. These data indicate that the latter sub-regions are in the most critical state from the scientific point of view.

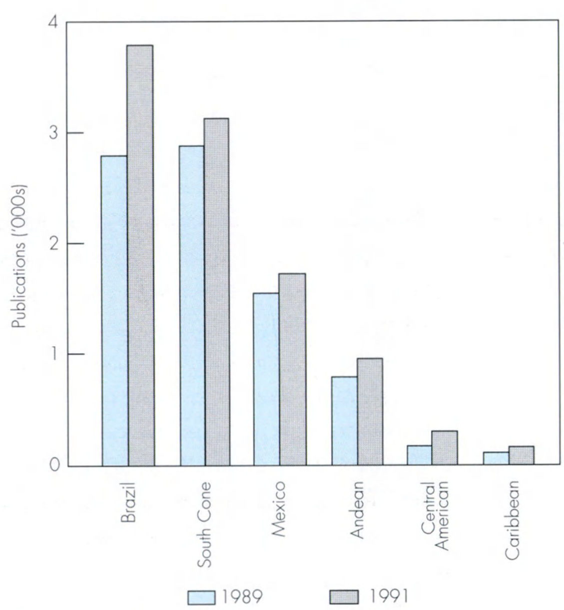
It is also interesting to study the 10 countries which, independent of their geographical location, produced the

FIGURE 10
PUBLICATIONS, 1991



Source: *SCI*, 1991.

FIGURE 9
PUBLICATIONS BY SUB-REGION, 1989 & 1991

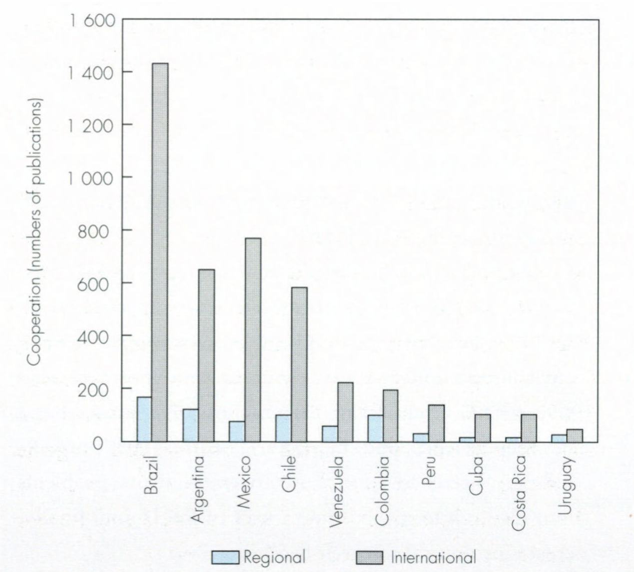


Source: *SCI-CDE*, 1989/91.

greatest number of scientific publications during 1991. As illustrated in Figure 10, the relative position of the 10 countries, in decreasing order according to net production in 1991, is as follows: Brazil, Argentina, Mexico, Chile, Venezuela, Colombia, Peru, Cuba, Costa Rica and Uruguay. In 1991, these countries produced 97.6% of the total scientific publications of Latin America.

In general terms, differences in the net scientific production within these countries seem to be related – as can be expected – to population size. However, the significance of other factors may become more evident when scientific production per million inhabitants is used as an indicator. Figure 10 also shows data corresponding to publications per million inhabitants for the same 10 countries. Here the relative positions of the countries change: Chile, Argentina, Costa Rica, Uruguay, Venezuela, Brazil, Mexico, Cuba, Peru and Colombia. It is also interesting to note that medium- and small-sized countries have higher scientific production values per million inhabitants than countries with larger populations. Investigation into the reasons for these results could provide some clues as to favourable factors for scientific development in Latin American countries, such as levels of basic education, economic situation, cultural influence of migratory flows, international cooperation and quality of the national science policy.

FIGURE 11
REGIONAL AND INTERNATIONAL COOPERATION, AS MEASURED BY JOINT AUTHORSHIP OF SCIENTIFIC PUBLICATIONS, 1990



Source *SCI*, 1990.

Scientific cooperation

We have considered, as an indicator of cooperation, the number of scientific publications produced jointly by researchers from two or more countries in Latin America in the case of regional cooperation, or from one or more countries of Latin America with researchers from countries outside the region in the case of international cooperation.

Figure 11 shows the results obtained from the evaluation of this cooperation, both regional and international, for each of the 10 countries selected according to scientific production. In every case, international cooperation is seen to be significantly greater than regional cooperation. It is expected, then, that regional cooperation should improve by that same measure as regional programmes of S&T cooperation advance, scientific development increases and communications improve.

NEW OBJECTIVES FOR SCIENCE IN LATIN AMERICA

As revealed by data presented in previous sections, most Latin American countries have of late only managed to stand still or at best to achieve a slow rate of growth. The relative position of countries from the scientific standpoint has also remained unchanged during the last few years. This suggests that if, in the short term, we expect to reach a significantly higher level than the one we occupy today, science policy needs to be revised and changed.

Factors hampering scientific development

In our view, the progress of science in Latin America is being hampered by a scarcity of human resources, a marked lack of economic resources, the relative isolation of researchers in certain fields of knowledge which are only slightly cultivated, and limited regional and international scientific cooperation. Furthermore, the poor relations between science and industry add to the difficulties.

For the most part, the lack of human resources is due to deficiencies in the educational system, the scarcity of scholarship programmes and low compensation schemes for R&D staff, all of which foster the abandonment of this kind of work and encourage researcher migration.

Moreover, although education is mostly free, the high cost of living denies access to higher education to more than four-fifths of the population. At the same time, isolation of researchers is common in all less developed countries where there are only a few individuals working on a common subject and, worse yet, where they hardly ever meet one another.

The scarcity of economic resources, both in absolute and in relative terms, is apparently linked to the limited interest shown by political and business leaders in local science, thus explaining the traditional neglect by governments and industry. Nevertheless, even politicians and industrialists with greater awareness of the role of science believe that scientists, in turn, often forget that Latin American countries have similar or more important and pressing problems requiring vast resources.

Clearly the most urgent problem in Latin America is the attainment of justice and social peace through the equitable distribution of wealth. This would facilitate internal social integration and the attainment of an acceptable quality of human life, and allow access for the whole population to the enjoyment of education, science and culture. Along the same lines, another urgent problem to solve is to find ways and means of consolidating regional and sub-regional integration processes crucial to the survival of Latin America as a region. Taking these considerations into account, an apparent controversy emerges periodically during discussions on the allocation of budgetary resources for science in the various countries and in regional and international agencies. This controversy seems to disappear as soon as it is realized that science and its applications are the most efficient means of attaining an equitable distribution of wealth, integration and, furthermore, development.

New objectives for science

In order to produce a quantitative and qualitative change in Latin American science similar to that which occurred during the two decades following the Second World War, it is imperative to design and implement new policies as bold as those adopted at that time. In what follows we put forward some ideas that could contribute to the design of these new policies for Latin America.

In our view, the new policies should have as their main objectives:

- The incorporation of science into Latin American culture, in an effort to overcome its current marginality.
- The building of a global Latin American scientific community, that would involve, personally or by means of telematic (i.e. telecommunications and data processing) networks, native Latin American scientists living abroad in research and advanced educational programmes being carried out in the region.
- The setting up of a Latin American scientific telematic network to overcome the isolation of scientists, especially of those working in frontier research fields.
- The consolidation of scientific and economic integration programmes.

The incorporation of science into culture

To achieve this goal, it seems that first we must:

- Strengthen basic scientific research, since it constitutes the very foundation of science.
- Incorporate science into education, particularly at the basic educational level, in order to make scientific knowledge available to the public at large; report and encourage public interest in science as a human activity and as a factor for cultural modernization; and promote discussion on the compatibility of science with social values and religious beliefs.
- Link science to the rest of the social systems and sectors, in particular those with strong scientific components, i.e. health, agriculture, communications, transport, energy, environment and natural resources, among others, and give special attention to the creation of a strong bond between science and industry. For this last purpose, industry needs to learn how to translate its problems into research terms, become a user of R&D and, finally, create intramural research facilities.
- Foster scientific cooperation and make science and its applications a fundamental component of the

integration process in progress, geared to expand in countries which, because of their size, human and economic resources, have a hard time developing.

Promote the creation of networks of laboratories and researchers working on certain frontier scientific topics, to mitigate the problem of isolation of scientists working in the newest areas of knowledge.

Disseminate throughout Latin America successful policies already tried and tested by several countries. To illustrate this, we could mention: the creation of ministries or secretariats of science and technology; the national research councils mentioned above; the Researcher's Career or the researcher promotion system; the scientist repatriation programme; graduate and scholarship programmes to cover postgraduate studies, post-doctoral assignments or training courses abroad; decentralization or regionalization programmes, and major provision programmes.

We must first implement the above-mentioned action in order to succeed in the integration of science and culture and, to this end, it is necessary that the S&T sector work in a coordinated and active manner with the other sectors, especially those of politics, education and economics. International agencies have a very special responsibility, particularly UNESCO, which has played such an important role in the quantitative and qualitative change undergone by Latin America during the decades since the Second World War.

A global Latin American scientific community

The scarcity of resources and isolation have been the fundamental causes of the growing migration of scientists from Latin America to the industrialized countries. It is an undeniable reality that an important and growing number of researchers have taken up residence outside Latin America. The severity of the present circumstances calls for us to extend the concept of the scientific community to include those scientists who have left their countries and gone to work elsewhere. This new concept of a global Latin American scientific community, different from that of a regional community, does allow us to conceive an ambitious programme of international scientific cooperation based on the potential role played by 'national scientists living abroad' in the development of science in their native countries and in the region.

The concept of a global scientific community, proposed by one of us (GC) at a recent council meeting of the Latin American Academy of Sciences (ACAL) in São Paulo, facilitates the design of a new model of regional scientific development: self-centred and extrovert at the same time which, without losing sight of the local, national and regional priorities, optimizes the cooperation of migrant scientists for the benefit of Latin America. To cope with the tasks implicit in this challenge, we can take advantage of the new telecommunication technologies; in fact, the academic telematic networks constitute a valuable instrument for tightening bonds with scientists living abroad. Using the academic telematic networks, ACAL, with the support of UNESCO, ICSU-COSTED, and the National Research Council of Science and Technology (CONICIT) of Venezuela, has developed databases and information systems with a view to implementing the concept of the global scientific community.

A Latin American scientific telematic network

The building of a telematic network to overcome the isolation of the scientists, especially those working in frontier research fields, is a challenge at the present time. The new communication technologies, telematic networks in particular, encourage the establishment of information flows between colleagues working in common areas. We are witnessing the beginning of a rapid evolution of the 'invisible college' as it is known, into a 'global electronic college'. In other words, from informal and sporadic contacts we are entering a new world of structured and continuous linkages.

The elimination of time-space barriers and the cost reduction brought about by academic telematic networks should help to mitigate the isolation to which researchers in developing countries have been subjected. The limited local interaction observed between colleagues in Latin American countries, due mainly to the small number of research scientists in the various areas of the frontiers of knowledge, could be overcome in part by the establishment of 'virtual critical masses' through contact offered by the networks.

Recently, *Union Latina*, in collaboration with UNESCO and ACAL, carried out a feasibility study on the Latin Union Academic Telematic Network of Latin America and the Caribbean (REDALC). Although competition will certainly continue to be a characteristic of the work of scientists, solidarity resulting from this new global electronic college should help to encourage the emergence of novel forms of cooperative research.

The consolidation of scientific and economic integration

The recent revival of integration processes, fostered by the formation of economic megablocks, creates an important framework for the design and implementation of multinational cooperation programmes in S&T. The economic integration projects of the Andean countries (*Pacto Andino*), Central America (MCCA), the Caribbean (CARICOM), the South Cone (MERCOSUR), as well as the Rio Group, the Group of Three (Colombia, Mexico and Venezuela), the Initiative of the Americas and NAFTA, should all foster the participation of scientists in the formulation of regional and hemispheric policies of cooperation.

Attempts should also be made to consolidate educational, scientific and technological, regional and sub-regional agreements to benefit the peoples of Latin America. However, an excessive emphasis on practical matters and applied knowledge, to the detriment of basic science, should be avoided. Thus Latin America's future during the 21st century will largely depend on the intelligently balanced consolidation of the education, scientific and economic integration processes.

CONCLUDING REMARKS

In this article we have presented a short survey of Latin America's past, mentioning briefly the pre-Columbian, colonial and independent periods, as well as events during the present century. We have been able to show that progress in science is intimately related to the development of the region and of its countries. The relationship between the flourishing of science in different decades, and political, economic and social situations, is easy to see. The greatest advance has been achieved in the present century, and great efforts have been made and are being made to avoid and overcome the effects of the present political, economic and social crisis that is weakening the region. We hope to come out of the crisis with a more solid basis for development, a better distribution of material goods between the whole population and an advanced state of regional integration, and to be more conscious of the role that science plays in the modernization of education, culture and of the economy. There are well-founded reasons for this optimism. In spite of everything, the gains made by science in Latin America in these last 50 years have been rematkable: the region can presently claim a total R&D population of 142 904 including researchers and associated professionals, 2 280 research units, an annual investment of US$5 320 million, the publication of 10 255 scientific papers and the implementation of 5 229 activities of international and regional cooperation.

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RAIMUNDO VILLEGAS is Chancellor of the *Academia de Ciencias de América Latina* (ACAL) and Professor at the *Instituto Internocional de Estudios Avanzados* in Caracas, Venezuela. He graduated as a Doctor in Medical Sciences from the *Universidad Central de Venezuela* and has been a Research Fellow at Vanderbilt University and Harvard Medical School, a Visiting Professor at Cornell University and a Visiting Scientist at the Dana Farber Cancer Institute in the USA. In Venezuela Professor Villegas served as Director of the *Instituto Venezolano de Investigaciones Científicas* and later as Minister for Science and Technology. He has been active on the International Council of Scientific Unions (ICSU), the International Union of Pure and Applied Biophysics and the ICSU Committee on S&T for Developing Countries.

GUILLERMO CARDOZA is Assistant Professor of International Economics and Technological Development at the *Universidad Central de Venezuela*, and Executive Secretary of ACAL. He is also editor of the newsletter *Cienca en América Latina* and a council member of the International Network for the Availability of Scientific Publications. Mr Cardoza graduated as a chemical engineer from the *Universidad Nacional de Colombia* and worked for some years in local industry, before doing his postgraduate training at the *Instituta de Estudias Superiores de Empresa* in Barcelona, Spain and at the *Université de Paris* in France. In 1991 he initiated the creation of the *Centro de Información y Estudio de la Ciencia de América Latina* at ACAL where he carries out research on Latin American science.

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WESTERN EUROPE

Sam Lloyd

Of all the regions of the world, Western Europe has the longest tradition of applying scientific thought to economy and industry and assuring its diffusion into all aspects of human existence. Its application led to the development of technologies of war and peace resulting in the exploration and later colonization of many parts of the globe, with an attendant dissemination of European cultural ideals. Meanwhile, those engaged in exploration and colonization brought home to Europe new knowledge of the world and its resources, and this, together with the contacts made with other cultures and reasoning, has enriched and refined European thought and philosophy over the centuries.

Today, those seeds of scientific thought have blossomed into 'hi-tech' industries throughout the world, the economic fruits of which sometimes seem to elude their European origins. How then should the status of science and technology in Western Europe be judged? Is European science to be considered as a pathfinder leading the rest of the world in the more intellectual pursuits, or is it perceived as having become self-satisfied and decadent? What efforts are governments making to meet the challenges of keeping Europe a world centre of scientific excellence in these days of instant communications?

To answer these questions it will be necessary to look not only at inputs in terms of investment, the fixing of priorities and the availability of a cultured, well-trained

TABLE 1
R&D PERSONNEL IN THE EUROPEAN COMMUNITY AND COMPARISONS WITH THE USA AND JAPAN

Country	R&D personnel (FTE) (1990)	R&D personnel per thousand labour force (1990)	R&D scientists and engineers (FTE) (1989)	R&D scientists and engineers per thousand labour force (1989)
Belgium	38 773	9.3	17 583	4.2
Denmark	25 070[2]	8.5[4]	10 962	3.8
Germany[1]	431 100	14.2	176 401	5.9
Greece	9 586[4]	2.4[4]	5 461	1.4
Spain	64 934	4.2	32 914	2.2
France	293 031	12.0	120 430	5.0
Ireland	11 379[2]	6.6[3]	6 340	4.9
Italy	144 917	5.9	76 074	3.1
Luxembourg	na	na	na	na
Netherlands	68 170	9.9	26 680	4.0
Portugal	12 043	2.5	5 456[2]	1.1[3]
UK	280 215[2]	9.8[3]	131 928[2]	4.6[3]
Eur 12[5]	1 379 218	9.3	610 229	4.2
USA	na	na	949 300	7.6
Japan	794 337	12.4	457 522	7.3

1. Germany does not include German Democratic Republic.
2. DGXII/A4 provisional estimate based on trends.
3. Refers to 1988.
4. Refers to 1989.
5. Eur 12 is total of available Member States – Luxembourg is not taken into account.
na: not available.

Sources OECD, DGXII/A4.

and proficient scientific workforce, but also at both the discoveries of the individual scientist and those of whole teams of scientists and technicians, who utilize the large installations needed to push forward the frontiers of astronomy, biotechnology or the physics of matter. In addition, there are the considerable teams of researchers engaged in generic enabling research who provide the background needed by the applied scientist engaged in direct industrial support.

GEOGRAPHICAL, ECONOMIC AND R&D GROUPINGS

Western Europe is a continent of extremely diversified geographical areas and coalescing economic alliances, together with developing political rapprochement. It encompasses nations ranging from small states like Monaco, the Vatican City and San Marino to the medium-sized economies of Germany, France, the UK and Italy.

Leaving aside the smallest nations, Western Europe is grouped into two main economic areas, the 12 states comprising the European Community (EC) – Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain and the UK – and the seven European Free Trade Area (EFTA) countries – Austria, Finland, Iceland, Liechtenstein, Norway, Sweden and Switzerland. Three further European states, traditionally uncommitted, are Cyprus, Malta and the former Yugoslavia. Turkey is associated with the EC, while Israel has a free-trade arrangement with the Community.

A further drawing-together of European states is now in progress with the closer association of the two major groups into a European Economic Area (EEA) consisting of the EC and EFTA countries, with the exception of Switzerland. Four of these states, Austria, Finland, Norway and Sweden, have applied for full membership of the European Community.

NATIONAL SCIENCE POLICIES

There are powerful cohesive forces, political, economic and social, creating a centripetal effect in the region. However, despite the large number of collaborative organizations and joint research and development (R&D) programmes, for historical or cultural reasons the various individual countries tend to have rather different approaches to S&T policy.

Before briefly examining attitudes in the four largest Western European states, several major objectives, common to all, should be mentioned. However, it is noted that even though the themes are universal, the approaches to their accomplishment are highly individual.

Firstly, the importance of research to industrial development and competitiveness has become increasingly apparent to all governments over the last two decades, and has assumed a high priority in their science policies.

Secondly, much thought has been given to questions of technology transfer to industry, particularly to small and medium-sized enterprises which are believed to be the main sources of innovation. Concurrently, the problems of intellectual property rights are seen to require delicate handling if such measures are to be effective.

Thirdly, within the constraints of fixed or at best slowly increasing budgets during the global economic stagnation of the current years, pressures have been applied by budgetary authorities at both national and international levels, to constantly appraise programmes, projects and organizations, the aim being to obtain maximum efficiency in terms of cost/benefit, wherever this can be defined, and to prune all possible unproductive dead wood. These actions have been found to be necessary in the face of the generally escalating costs of S&T activities.

Fourthly, all countries recognize the many advantages that accrue from international cooperation and provide for it in their policies, both scientific and diplomatic.

Lastly, the education and training of scientists, technicians and engineers in universities, colleges and laboratories in the field, or on the shop floor, is a permanent and high priority feature in all national strategies.

France

In France, research and technological policy issues are predominantly centralized under the Minister for Research and Technology, who is directly responsible for govern-

TABLE 2
R&D INVESTMENT ACROSS THE EUROPEAN COMMUNITY AND COMPARISONS WITH THE USA AND JAPAN

Country	Total GERD (ECU millions)	GERD as % of GDP 1991	GERD per capita population (ECU) 1991	% of GERD 1990 financed by			% GERD 1990 performed by		
				Government	Industry	Other	Government sector	Business enterprise sector	Higher education and other sectors
Belgium	2 722[1]	1.71	272	27.6	70.4	2.0	6.1	72.6	21.3
Denmark	1 675	1.59	325	45.5[3]	46.8[3]	7.7[3]	19.1[3]	55.0[3]	25.9[3]
Germany[2]	35 519	2.58	445	37.2[4]	59.9[4]	2.9[4]	15.2[4]	68.4[4]	16.4[4]
Greece	402[1]	0.70	39	68.9[3]	19.4[3]	11.7[3]	42.4[3]	22.3[3]	35.3[3]
Spain	3 730	0.87	96	45.1	47.4	7.4	21.3	57.8	20.9
France	23 511	2.42	412	48.3	43.5	8.2	24.2	60.4	15.4
Ireland	340[1]	0.97	96	29.0	60.0	11.0	16.2	60.7	23.0
Italy	12 821	1.38	224	51.5	43.7	4.8	20.9	58.3	20.7
Netherlands	4 630	2.00	307	45.1	51.1	3.8	18.1	56.2	25.7
Portugal	399[1]	0.72	41	61.8	27.0	11.1	25.4	26.1	48.4
UK	18 435[1]	2.26	320	35.8	49.5	14.8	14.0	66.6	19.3
Eur 12[5]	104 184	2.02	302	41.2	51.7	7.1	17.4	64.5	18.1
USA	124 559	2.78	493	47.1	50.6	2.3	11.0	69.9	19.1
Japan	77 700	2.86	627	16.1	77.9	6.0	8.0	75.5	16.6

1. EC provisional estimate based on trends.
2. German Democratic Republic is included in the data for Germany.
3. Year of reference is 1989.
4. Year of reference is 1991.
5. Eur 12 is total of available Member States. Luxembourg is not included: data not available.

GERD: Gross Domestic Expenditure on R&D

Sources: OECD, EUROSTAT, ECDGXII/A4.

ment research establishments and research bodies funded from the civil service research and technological development budget, such as the National Centre for Scientific Research (CNRS). He also shares joint responsibility with other Ministers for a whole range of S&T organizations such as the National Institute for Health and Medical Research (INSERM), and the National Centre for Space Studies (CNES).

The Minister for Research and Technology chairs the Superior Council for Research and Technology and is consulted on the research programmes of state-owned enterprises.

In France, special efforts are focused on providing a new impetus to basic research, the stricter management of major technological development programmes and increasing the general level of technology as a whole.

Industrial research enjoys both direct and indirect government support. Direct aid is open to firms selected to participate in one of the 11 technologies selected under the National Programmes devised to promote industrial know-how and bring together industrial research departments and the public laboratories. Technological Development Programmes have been set up in the priority areas of civil aeronautics, space, civil nuclear power, telecommunications and the major defence programmes; all are entirely state funded. Indirect support is provided in the form of tax concessions which are made available to provide indirect aid to enterprises undertaking R&D in order to stimulate industry. An improved synergy between civil and defence

TABLE 3
GOVERNMENTAL FINANCING OF R&D IN THE EUROPEAN COMMUNITY, 1991, AND COMPARISONS WITH THE USA AND JAPAN

	R&D financing by governments	
Country	Civil (%)	Defence (%)
Belgium	99.8	0.2
Denmark	99.6	0.4
Germany[1]	89.0	11.0
Greece	97.6	2.4
Spain	83.2	16.8
France	62.6	37.4
Ireland	100.0	0.0
Italy	92.1	7.9
Netherlands	96.5	3.5
Portugal	99.1	0.9
UK	55.7	44.3
Eur 12[2]	77.9	22.1
USA	40.3	59.7
Japan	94.3	5.7

1. German Democratic Republic is included in the data for Germany.
2. Eur 12 is total of available Member States. Luxembourg is not included: data not available.

Source OECD.

R&D programmes (financed 63% and 37% respectively by the government) is sought (see Table 3).

The long-term target is to increase the gross domestic expenditure on R&D (GERD) from 2.4%, representing ECU23 511 million (the ECU is the European currency unit) in 1991, to 3% as soon as possible.

Germany

The German system is rather different. Responsibility for S&T is divided between the federal government, for non-university basic research and industrial sector international cooperation, the governments of the individual states (*Länder*) for the universities and medical schools and the independent science institutions including the German Research Society (DFG), the Max Planck Society (MPG) and the Fraunhofer Society (FhG), and the Union of Large-Scale Research Organizations, for the rest.

Federal responsibility falls on the Federal Minister for Research and Technology (BMFT) who is aided by the Bundestag Committee for Research and Technology, with control and monitoring functions. In laying down guidelines for research policy, the federal government consults the independent research institutions DFG, MPG and FhG, the latter being responsible for linking science to industry. Apart from the direct responsibilities outlined above, the BMFT has shared responsibilities for research in areas falling under the charge of other Ministers. An example is the innovation framework for small and medium-sized enterprises which he shares with the Minister responsible for industry.

A major reappraisal occurred with the reunification of the former West and East Germanies which began in 1989. The centralized scientific structure of the German Democratic Republic, dominated by the Academies of Science, of Agricultural Science and of Civil Engineering and Architecture, was converted to the structure existing in the Federal Republic of Germany following an evaluation of the entire former East German scientific community.

Great emphasis is placed on the principle of 'freedom of research' and the importance of individual initiative with the promotion of a scientific elite. Direct and indirect government aid is available for the stimulation of industrial R&D, with special attention given to the small and medium-sized enterprises where research staff costs are subsidized. Germany spent ECU35 519 million on R&D in 1991, which is 2.6% of its gross domestic product (GDP). Civil activities absorbed 89% and defence R&D 11% of the total.

Italy

In 1989, Italy introduced profound changes to its S&T structure with the creation of a Ministry for Scientific and Technological Research and the Universities (MURST), as a single decision-making body to coordinate all publicly funded research. Furthermore, universities and other research institutes now enjoy a large measure of independence in their choice of research programmes and in the management of their resources.

The Minister is helped in his task of planning scientific policy by the Inter-Ministerial Economic Planning Committee and the Inter-Ministerial Industrial Policy Committee, and is advised by the National Science and Technology Council (CNST), a body of high-level members of the scientific community. The national university council (CUN) is concerned with the management of universities. In addition to the MURST, other Ministries, such as the Ministry for Defence, the Ministry for Industry and the Ministry for Special Assistance to Southern Italy, also help to finance research in their area of competence.

Somewhat similar to the French CNRS, the Italian National Research Council (CNR) is a multidisciplinary research organization particularly concerned with managing projects targeted by government R&D policy. These applied research projects are concerned with themes of national interest and are executed by various governmental, industrial, regional and local organizations in areas such as industry, agriculture, energy, health and the environment.

The principal objective in Italian science policy is to raise the level of research to one comparable with other European countries of similar GDP such as France or the UK. To achieve this goal, investment growth is directed towards improving the quality of the system, and the balance between various types of research, between the various sectors and between the north and south of the country. The capacity for participation in international and European programmes is being increased and industrial R&D encouraged by means of tax concessions.

In 1991 the total GERD was ECU12 821 million, 1.4% of the GDP. Of this, 92% was spent on civil R&D and 8% on defence.

TABLE 4
THE TECHNOLOGY BALANCE OF PAYMENTS IN THE EUROPEAN COMMUNITY, 1990, AND COMPARISONS WITH THE USA AND JAPAN

	Technology balance of payments		
Country	Receipts (ECU millions)	Payments (ECU millions)	Balance (ECU millions)
Belgium	1 480	1 973	−493
Denmark	na	na	na
Germany[1]	4 268	5 156	−887
Greece	na	na	na
Spain	315	1 716	−1 400
France	1 493	2 004	−510
Ireland	na	na	na
Italy	555	965	−410
Netherlands	504	947	−443
Portugal	na	na	na
UK[2]	1 788	1 865	−77
Eur 12[3]	10 405	14 625	−4 220
USA	12 936	2 461	10 475
Japan	1 848	2 025	−177

1. Germany does not include German Democratic Republic.
2. Year of reference is 1989.
3. Eur 12 is total of available Member States (including 1989 data for UK).

Sources: OECD, EUROSTAT, DGXII/A4.

The United Kingdom

Until 1992, the central scientific structure in the UK had consisted of 11 government departments answering to the Cabinet and the Prime Minister. This changed with the appointment of a Minister for Science and the publication of a national strategy for science based on a partnership between industry, scientists and government. The strategy, prepared by the Office of Science and Technology (OST), will be endorsed annually by the Cabinet and will include allocations for the year's expenditure and a 5-10-year projection of likely trends in science. Prime objectives of the national science strategy are to improve the quality of life and to increase the nation's wealth.

A radical departure from the previous policy, in which all near-market R&D was the responsibility of industry, is seen in the intention to support some promising research lines which fail to receive commercial backing. However, tax advantages to enterprises undertaking R&D are not available.

In the light of changed needs, a searching review is being made of all government-funded research organizations in order to identify those that should be retained, those suitable for privatization and those which may be discontinued.

Research grants are awarded to peer-reviewed projects by seven sector-based Research Councils, and separate Higher Education Funding Councils support the universities. In 1991, the total GERD amounted to ECU18 435 million, representing 2.3% of the GDP, and of which 56% is allocated to civil and 44% to defence R&D.

From the above it is clear that the importance of a thriving S&T base is now considered to have very high priority in the drive for prosperity and social well-being in Western European countries, and that national governments, highly conscious of this, are frequently reviewing and updating their policies to meet the new circumstances stemming from an evolving Europe.

SCIENTIFIC OUTPUT

A common factor in scientific activities is the communication essential to all except perhaps the industrial scientist, whose work is governed by commercial considerations. This communication process is most conveniently accessed and analysed via publications appearing in the scientific journals of international repute. The method should only be considered as qualitative since it ignores the mass of data issued in 'grey' literature such as technical reports aimed at particular research areas and the increasing amount of knowledge in databases throughout the world.

At the same time, distortions can occur due to a perceived need to be up-to-date, as noted in a 'bandwagon' effect where a press release or a provocative preliminary publication may lead to a burst of literary activity, either speculative or objective and factual, which can numerically falsify the actual state of knowledge on a particular subject. In this respect, claims and counterclaims surrounding 'cold' fusion serve as a cautionary example. Nevertheless, the use of citation indices does make possible a qualified comparison between the weight of similar activities in different geographical areas. The following section will attempt to sum up published scientometric data available on Western Europe.

Another traditional method of assessing scientific vitality is by means of the number of scientists receiving international prizes, in particular the Nobel Prize. Between 1945 and 1992 Western European scientists were awarded 112 Nobel prizes (in physics, chemistry, and physiology or medicine) compared to the 143 gained by those of North America and five by Japanese scientists. If we take the economic sciences into account, these figures become 123, 162 and five respectively.

The published results

The region as a whole publishes slightly more than 33% of the world's output of scientific literature (in physics, chemistry, mathematics, the life sciences and the engineering sciences), as compared to over 40% for North America (USA and Canada) and 7% for Japan. The 'top ten' in descending order of world output in all fields are the UK, Germany, France, Italy, the Netherlands, Sweden, Switzerland, Israel, Spain and Belgium, together publishing 30%. It is interesting to note that the 12 European Community Member States as a group produce some 28% of the world output in scientific literature.

Turning to output in the major scientific fields, the ranking differs for each subject, as might be expected.

In physics the order is Germany, the UK, France, Italy, the Netherlands, Switzerland, Israel, Spain, Sweden and Belgium, with a total output of 28% of global output.

Germany, the traditional birthplace of chemistry, leads that field, followed by the UK, France, Italy, Spain, the Netherlands, Switzerland, Sweden, Belgium, Israel and Finland, and together they represent 30% of world publishing in the subject.

Mathematics is also led by Germany, with France, the UK, Italy, Israel, the Netherlands, Spain, Belgium, Switzerland and Sweden adding up to 30% overall.

The life sciences are ranked the UK, Germany, France, Italy, Sweden, the Netherlands, Israel, Switzerland, Denmark and Belgium, totalling 33% of the published output.

The order for the engineering sciences is Germany, the UK, France, Italy, the Netherlands, Switzerland, Israel, Sweden, Spain and Belgium, with a combined world output of 26%.

Apart from ranking individual countries in the area on the world scene, it is also of interest to explore the way in which scientific output is distributed within national totals to get some feeling for the importance attached to the various fields of scientific activity in the countries concerned.

Taking the region as a whole, the life sciences can be seen to predominate over all other scientific disciplines, representing a mean value of 57% for all countries in Western Europe. The traditional interest shown in these themes by the Scandinavian countries is illustrated by values of more than 70% for Denmark, Finland, Norway and Sweden. At the other end of the scale, one finds Greece, Portugal, Spain and Turkey with proportions of 39% to 45% of their total output.

Publication in physics represents more than 20% of the national totals for the former Yugoslavia, Greece, Portugal, France, Switzerland and Italy, down to 10% in the case of Sweden. In all countries, physics is found to be the second most important output, except in the case of Spain which shows a strong preference for chemistry, at 30% of its output. A second group consisting of the former Yugoslavia, Germany and Italy fall into a 20% category, and the Scandinavian countries appear the least active.

Mathematics, by its nature, has a smaller following everywhere but at the same time is not restricted by the need for expensive apparatus or infrastructure. In most countries the discipline accounts for only some 2-3% of the national output. However, Austria, Italy, France and Turkey all lie between 3% and 4% and Greece, Israel and Portugal all above 4%.

Finally there are the engineering sciences, to which some of the apparently less favoured countries appear to attach considerable importance. In Turkey, Greece, Portugal, the former Yugoslavia, Germany and Austria engineering contributes 10-20% of total national output.

These comparisons reflect not only the drive towards

TABLE 5
NATIONAL PATENT APPLICATIONS IN THE EUROPEAN COMMUNITY, 1990, AND COMPARISONS WITH THE USA AND JAPAN

Country	National patent applications			External applications by residents
	Total	Resident	Non-resident	
Belgium	43 544	912	42 632	7 947
Denmark	35 998	1 288	34 710	10 240
Germany[1]	95 164	30 928	64 236	161 006
Greece	18 765	389	18 376	536
Spain	46 817	2 260	44 557	4 603
France	78 919	12 742	66 177	66 632
Ireland	4 735	734	4 001	1 226
Italy	na	na	na	29 969
Luxembourg	32 591	41	32 550	955
Netherlands	49 989	2 646	47 343	26 351
Portugal	3 642	101	3 541	86
UK	90 978	19 474	71 504	80 320
Eur 12[2]	344 043	71 515	272 528	199 531
USA	175 333	90 643	84 690	295 202
Japan	376 371	332 952	43 419	129 835

1. Germany does not include German Democratic Republic.
2. Eur 12 is total of available Member States. Italy is not taken into account in columns 1-3.

na: not available.

Sources: OECD, DGXII/A4.

pre-eminence in 'Big Science' by the more industrialized countries, and the echoes of very long-term traditional interests in the various fields, but also the influence of social structures and the existence of well developed universities and perhaps an adequate national research infrastructure. The great diversity among the European nations with their differing scientific traditions could lead one to consider the area a veritable scientific 'gene bank'.

The patent scene

Yet a further measure of the region's diversity in scientific and technological (S&T) activity can be obtained by examining the output in annual patents granted per 100 000 residents for various countries.

Averaging the number over the three years from 1987 to 1990 it is found that the leader of the field is Switzerland with 40.44 patents per 100 000 population, which is second only to Japan (with 43.44). Germany and Sweden follow with 28.14 and 22.91 respectively, as compared to 19.12 for the USA. Next come Austria, Finland and France all with scores above 15, and a large group comprising the UK, Norway, Denmark, the Netherlands, Belgium, Greece and Spain, lying between 7.7 and 4.4, and finally Ireland, Italy, Portugal and Turkey which file less than 1 patent per year per 100 000 residents.

Looking at the trend for the period 1985-90, the annual number increased in Denmark, Ireland, Finland, Germany, Norway, Austria, the Netherlands, Spain and Sweden, and decreased in Switzerland, France, Turkey, the UK, Portugal, Belgium, Greece and Italy. The rate of increase/decrease ranged from 12.7% at the top of the list to –11.7% at the bottom.

In general, the correlation with other indicators is not altogether clear-cut and appears to reflect the relationship of publication habits with the relative level of technological industry rather than the degree of scientific culture in a country.

TABLE 6
PERCENTAGE SHARES OF WEST EUROPEAN PATENTING IN THE USA, 1963-88

	1963-68	1969-73	1974-78	1979-83	1984-88
Germany[1]	33.74	35.62	37.16	40.10	40.91
UK	24.80	21.56	18.16	15.91	14.67
France	13.42	13.99	14.45	14.29	14.60
Netherlands	4.67	4.36	4.32	4.49	4.62
Italy	4.27	4.77	4.72	5.37	5.83
Denmark	0.92	1.08	1.03	0.93	1.03
Belgium	1.63	1.88	1.84	1.64	1.55
Ireland	0.06	0.14	0.11	0.12	0.20
Spain	0.42	0.47	0.59	0.40	0.57
Greece	0.06	0.08	0.07	0.04	0.05
Portugal	0.03	0.03	0.03	0.02	0.02
Switzerland	8.66	8.41	8.81	8.33	7.31
Sweden	5.24	5.08	5.65	5.09	4.89
Austria	1.33	1.57	1.76	1.85	1.89
Norway	0.50	0.53	0.62	0.56	0.60
Finland	0.25	0.42	0.68	0.85	1.27
Total	100.00	100.00	100.00	100.00	100.00

1. Germany does not include German Democratic Republic.

Source: US Department of Commerce, Patent and Trademark Office.

SCIENCE IN THE EUROPEAN COMMUNITY

One result of the drawing together of European states has been a number of actions in scientific and technological programmes under EC science policy, grouped together under a multiannual Framework Programme with the aim of strengthening the scientific and technological basis of European industry and of encouraging it to become more competitive at the international level. First launched in the early 1980s with the philosophy of effecting at Community level all research which is more appropriately and more efficiently conducted there, the Framework Programme has steadily evolved and grown during the first three exercises, and a fourth programme was under negotiation in mid-1993.

The ongoing third Framework Programme for 1991-94 has a budget of some ECU6 600 million as compared to ECU5 396 million for the previous one, and operates in three main areas: enabling technologies, including information technologies and industrial and materials technologies; management of natural resources comprising environment, life sciences and energy; and management of intellectual resources consisting of human capital and mobility, a programme mainly concerned with the creation of a genuinely European scientific potential and workforce. The budget represents less than 5% of the overall budget of the European Communities and is of a similar order of magnitude to the total expenditure on R&D in the 12 Member States. For the fourth Framework Programme, the European Commission is proposing to allocate a sum of ECU13 100 million to reduce the fragmentation of its present efforts and to improve the translation of S&T achievements into economic and commercial successes.

The Framework Programme also has provision for cooperation in Community research, technological development and demonstration with third-party countries and international organizations, while research is also included within the ambit of the agreements accompanying the Treaty establishing the EEA.

Research activities covered by the Framework Programme are implemented in three different ways.

The first form of Community research is *'extra-muros'*, i.e. research based on 'shared costs'. The EC defrays a substantial part of the costs of the work carried out, the other part being borne by the performer (research centre, university or industrial enterprise). This type of research is the major one in terms of scale, and is considered to be an extremely important way of strengthening the technological competitiveness of Europe. It provides the opportunity to make use of the research teams and laboratories in the Member States and to reap the synergistic benefits of putting together different teams on the same research objective. It is thus a potent means of coordination.

Second, 'in-house' research is carried on at the four sites of the Community's Joint Research Centre (Ispra in Italy, Geel in Belgium, Karlsruhe in Germany and Petten in the Netherlands). The JRC is particularly suited to research aimed at underpinning Community regulatory and normative activities connected with economic, industrial and social policies. It has a natural vocation for research on cross-boundary problems, such as those related to the environment and risk analysis. It is also well placed to perform research that is, by definition, international, e.g. creating standardized reference materials and measurement techniques, providing large-scale test facilities for use by scientists from Member States of the Community, thus guaranteeing a long-term commitment to research considered to be in the interest of Europe, and ensuring equal access to all Member States.

Finally, certain Community activities (such as the medical research programme) take the form of 'coordinated actions'. No transfer of funds takes place, the individual elements of the programme being furnished by Member States which finance national projects and are responsible for their implementation. The Commission of the European Communities looks after coordination, by promoting the exchange of information, and meets the costs this entails. Concerted action makes it possible to tap the diversity of skills and traditions available in the Community, with little outlay of funds and interesting effects of cross-fertilization. The Framework Programme includes actions to promote the training and mobility of young scientists and engineers. These grants are mainly directed to postdoctoral research and are open to EC nationals. In principle, the work has to be performed in a Member State other than the country of the grantee.

In the fourth Framework Programme, the Commission's proposal identifies six broad aims:

Greater integration of national, Community and European activities.

Greater selectiveness with regard to Community research, development and technology activities in order to increase economic impact.

Dissemination and optimization of results of activities in Community research, technological development and demonstration.

Development of research/training synergy.

Development of synergies between research policy and economic and social cohesion policies.

Increased flexibility of Community activities in order to respond rapidly to new S&T changes.

All international scientific cooperation is included within the Framework Programme and better integration of European research is encouraged by the establishment of coordinating links with national programmes, Community programmes and EUREKA (see p. 55), as well as other European bodies for scientific cooperation. The Joint Research Centre, the EC's own research centre, could play a role as the focal point of the network.

OTHER INTERGOVERNMENTAL ORGANIZATIONS

At the end of the Second World War, the movement towards international collaboration in science gathered strength, with the creation of the United Nations Educational, Scientific and Cultural Organization (UNESCO), followed by a number of other specialized agencies of the United Nations system such as the Food and Agriculture Organization (FAO), the International Atomic Energy Agency (IAEA), the World Health Organization (WHO) and the World Meteorological Organization (WMO), all of which are concerned with scientific research in one way or another. UN inspired organizations have had a particular influence on the relations Europe enjoys with the rest of the world in the realm of scientific endeavour.

Another organization that has had a significant influence on European scientific life in the nuclear R&D area is the Organization for Economic Cooperation and Development (OECD), with its Nuclear Energy Agency (NEA) which, among other activities in the latter years of the 1960s, built experimental reactors at Halden in Norway and at Winfrith Heath in the UK, and a reprocessing plant for highly enriched nuclear fuel at Dessel in Belgium. The first of these installations is still in operation and engaged in research.

The North Atlantic Treaty Organization (NATO), based in Brussels in Belgium, brings together most European countries, with the USA and Canada, for the purpose of collective defence. However, in 1957 NATO established its Science Programme to seek to advance the frontiers of science generally and to promote participation in research by NATO nations. Since its inception, over half a million scientists from the Alliance and other countries have participated in this action through international exchange programmes focusing on the individual scientist rather than institutional involvement.

The European scene would not be complete without mention of the International Standards Organization (ISO), made up of national standards bodies and operating through the consensus of a series of working groups and expert committees. In Europe the standardization bodies have set up the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC) and, as the Western European area becomes more united, the degree of scientific refinement required to produce workable and reasonable standards is multiplying.

Turning from international to European intergovernmental organizations (IGOs), CERN, the European Centre for Nuclear Research was set up in 1953 in Geneva, Switzerland, its foundation having taken place at a meeting organized by UNESCO in 1951. Since that time CERN has gone from success to success and become a household word throughout Europe. It can certainly be considered as the most influential of the various European collaborations. Apart from its notable scientific achievements and the level of engineering demonstrated in that most exacting field of construction and operation of very large, high-energy physics experiments, CERN has been the model for a number of other scientific research organizations.

One such is the European Southern Observatory (ESO) established at Garching in Germany in 1962. Its main tasks have been to provide European astronomers with telescopes to scan the Southern Hemisphere from a number of observatories. ESO plays a leading role in observational instrument development with its New Technology Telescope (NTT), the first to use computer steered or 'active optics' to improve image sharpness. The system will be used in the Very Large Telescope (VLT) to be completed in the last years of the century.

The other significant CERN offspring is the European Molecular Biology Laboratory (EMBL) which was set up in 1974 under the auspices of the European Molecular Biology Organization (EMBO), itself founded in 1964. The laboratory opened in Heidelberg in Germany in 1977 and quickly gained a reputation for the quality of its scientific and technical output and, like CERN, became noted for its value in training young research scientists. Recently, a new outstation in Cambridge, UK, the European Bioinformatics Institute (EBI), has been added to its other two outstations at the *Deutsches Elektronen Synchrotron* (DESY) in Hamburg, Germany, and at the *Institut Laue-Langevin* in Grenoble, France. A further detachment is planned at the European Synchrotron Radiation Facility (ESRF) also in Grenoble.

A very successful European organization strongly associated with science is the European Space Agency (ESA). Launched in Paris in 1973 by merging the European Space Research Organization (ESRO) and the less successful European Space Vehicle Launcher Development Organization (ELDO) which had been set up in 1962, ESA runs a highly successful scientific programme of which the comet research satellite *Giotto* is a notable manifestation. The programme is based on four 'cornerstones': solar terrestrial physics, planetary missions, X-ray spectroscopy and millimetre-wavelength radio spectroscopy. ESA also operates a business, launching some 50% of the world's commercial payloads for telecommunications, Earth-observation and meteorology using its very successful *Ariane* launcher. There is considerable European spin-off into applied science in agricultural statistics and crop forecasting, in weather forecasting and in oceanographic and environmental studies using improved techniques.

The most recent Europe-wide collaboration was set up in 1985 at the instigation of the French Government and is named EUREKA. This programme is mainly concerned with near-market research and participants in agreed pan-European projects seek funding from their own governments. The programme is much less centralized than EC actions and adopts a more 'bottom-up' approach. At the present time, there are about 675 ongoing projects distributed over nine high-tech areas.

It can be seen that despite the growth of the European Community and its Framework Programme, a number of other intergovernmentally financed organizations and agencies continue to coexist, and in many cases to thrive. While Community programmes are directed towards improving social conditions in the Community and enhancing industrial competitiveness in the world at large, many of the other IGOs serve specific fields of science requiring large, expensive equipment or intensive cross-fertilization. EUREKA is a special case in that it avoids many of the criticisms of being top-heavy and remote from the field of action. It is too soon to make any real assessment of its success in meeting the industrial challenge, although in terms of cross-frontier collaboration between its 20 member countries it has shown itself to be workable. If one considers the Big Science projects, with their tendency to expand to ever-larger projects, one sees increased worldwide collaboration particularly with North America and frequently a desire to seek new partners outside the original spheres of influence. This is exemplified by the EC Fusion Programme's Joint European Torus (JET) project at Culham, in the UK, which is at present coming to a successful conclusion. The next large fusion experiment is likely to be on a world scale, since the financial demands exceed those reasonably available within the joint funding of the European partners. Currently, the most promising project appears to be the International Thermonuclear Experimental Reactor (ITER).

In summary, we may say that the IGOs are mainly concerned with basic research, the EC programmes embrace pre-competitive research, while EUREKA activities belong to the near-market research category.

NON-GOVERNMENTAL ORGANIZATIONS

During the second half of this century, a whole host of international non-governmental organizations (NGOs) were established to provide the advantages of collaboration in all aspects of scientific endeavour. Their number is considerable and we attempt here to present only a representative sample of organization types which range from international organizations serving world science in general, such as the International Council of Scientific Unions (ICSU), through those having a strictly European and monodisciplinary scope, such as the Federation of European Biochemical Societies (FEBS), grouping national societies, to those concerned more directly with the scientist as an individual such as the recently born Academia Europaea, a forum for distinguished scientists, or the long-established monodisciplinary European Physics Society. All these types of association serve to provide communication between scientists on an open or more or less exclusive basis in cases where IGOs would be too cumbersome or inappropriate. The approach is often more 'bottom-up' than activities governed by the dictates of government or Community-inspired science policies.

Perhaps the most influential NGO in the European context is the European Science Foundation (ESF). This was set up in Strasbourg, France, in 1974, and brings together 59 national and international public-grant providing organizations and research institutes from 21 Western European countries. Membership includes national research councils, the EC, and distinguished scientific organizations such as Germany's Max Planck Society, the French National Centre for Scientific Research (CNRS) and the UK's Royal Society.

The ESF has been particularly successful in launching collaborative projects such as the 6-GeV European Synchrotron Radiation Facility (ESRF) at Grenoble in France. Construction of the project began in 1989 and it is expected that a few beam lines will be operational in 1994. The complete set of 30 beam lines is scheduled for completion in 1998. The group of partners comprises France, Germany, Italy and the UK as principal contributors, together with Spain, Switzerland, the Nordic countries and Belgium. When commissioned, the machine will be the most powerful synchrotron source in the world, although an even more powerful 7-GeV machine is under construction in the USA.

Another collaborative project of a quite different nature is the European Geophysical Traverse, in which institutes in a number of European countries are joined together in a research network for a comprehensive investigation of the Earth's crust from the north of the continent to the Euro-African boundary. This ESF initiative is one result of the Foundation's seminal interest in the idea of the use of networks in the pursuit of research by linking scientists in different institutes and countries in Europe to carry out common projects or to pool knowledge. At present there are 27 ESF networks covering subjects ranging from communications and transport to quantum liquids and solids, with general emphasis on the life sciences. The idea has been taken up on both national and European scales by many organizations and is the mainstay of many EC actions in fields as diverse as medical research and materials R&D.

Grenoble is also host to the *Institut Laue-Langevin* (ILL) which operates the high-flux beam reactor (HFR), the world's highest performance reactor for neutron beam experiments. The management is shared by a partnership of France, Germany and the UK. Again, a networking principle is applied in the utilization of the machine, which is much too costly to be used by one group of scientists.

The recently EC-sponsored International Association for the Promotion of Cooperation with Scientists from the Independent States of the former Soviet Union is particularly important now in making links with scientists to help avert the total collapse of scientific activity in the very difficult and uncertain economic climate of the next few years in those countries. The Association is composed of the 12 EC countries together with the European Community and 12 states from the former Soviet Union. Recently, Austria has joined the Association.

With the very strong emphasis in Western Europe on harnessing science and technology to contribute to a more competitive industrial base, it is hardly a surprise to find, alongside national and EC policies, initiatives coming from industry and the investment sector. The European Round Table is an NGO comprising financiers and the heads of major European industries engaged in the manufacture of products with a high technological content. By transmitting their opinions to governments and the EC, this group inject a measure of 'market pull', thus providing a foil to the tendency to 'technology push' shown by the more purely scientific advisers.

EVOLUTION AND PUBLIC PERCEPTION

Taken generally, government science policy as practised in the larger European countries over the last few decades has shown an evolution in which the rise of large publicly funded research centres has mostly given way to their eclipse.

During the mid-1930s, the world of the lone individual scientist in his or her own laboratory, especially where the physical sciences were concerned (also in many life science areas), was overtaken by the need for ever-more sophisticated equipment as more complex and intractable experimental problems were tackled, and technological progress supplied tools to facilitate fresh approaches or to bring greater precision to results.

The largest research establishment, usually owned and operated by the government or a multinational company, was frequently the product of experience gained in providing the R&D support needed to meet military requirements in the Second World War, followed by the rapid expansion of the civil nuclear R&D sector in the quest for safe and reliable atomic power sources.

Research centres were multidisciplinary, and in many parts of Europe became the established choice for tackling everything from technical problems in agriculture to engineering R&D. The management of science became a profession in itself to handle the matrix structures needed to enable large projects to be broken down into their disciplinary components for execution by the various teams of specialists.

However, as the programme aims were accomplished, the scale of scientific manpower engaged in single R&D projects became more modest. Project-oriented R&D was often replaced by programmes of a more generic nature, and revised priorities and economic pressures encouraged governments to evaluate the appropriateness of such teams of scientists.

Early attempts at applying cost/benefit analysis as used in assessing engineering projects, tended to produce only qualitative results due to the difficulty in defining meaningful input parameters and of measuring output, scientometrics being mainly concerned with accessible output through literature surveys and citation analysis. Even in the case of industrial research, financial effects, if any, can only be analysed fully when production, marketing and other costs are known.

Peer-review systems have therefore come into prominence and need, quality and programme management efficiency have become the principal criteria for judging programmes. Following stringent scrutiny, many of the large establishments have been reduced or subdivided into units of more manageable size better suited to the tasks in hand, and in some cases privatization of former publicly owned units has followed.

One result of this change is that scientists and technicians, less buffered from the outside world, have learnt to be more flexible in their attitudes to the type of work they undertake, and some degree of contract research has become the norm for many teams engaged in basic studies. In some cases this is resulting in enrichment through cross-fertilization, but in others scientists have been lost to commerce or to other occupations.

Employment market pressures also encourage the mobility of research staff who are becoming more accustomed to short-term contracts in Europe instead of the 'tenure for life' so much a feature of direct grant research in the past. At the same time, a 'brain drain' is provoked in young postgraduate scientists unable to find employment in Europe, although in countries such as Greece and Ireland this has always been a feature of scientific life where graduate supply has tended to exceed demand. In this respect, the international centres of scientific excellence, like CERN, have done something towards redressing the situation, by constituting 'brain parks' for some of the more talented.

Other pressures for reform result from the demand for more transparency in governmental activities from a public whose perception of science and the scientist has undergone a parallel evolution.

Originally, the largely scientifically uneducated and essentially tradition-bound European public saw the scientist in the comic mould of the 'mad professor' or as a sort of magician engaged in the business of providing new marvels to an admiring world but of little other significance. In a sense, this was changed by the Second World War when technology was demonstrated to provide the sophisticated offensive and defensive devices so painfully endured by the civilian population in Europe.

With the opening of the Pandora's Box of nuclear energy, a period of euphoria followed during which the scientist was expected to provide society with limitless, virtually free, energy. At the same time, scientists were also perceived to have been the authors of mass destruction, and thus dangerous and out of control. Some of the more eminent scientific personalities of the day were acutely aware of this 'loss of innocence' and began the continuing preoccupation with the implications of scientific activities on moral and social well-being.

Similar scenarios developed in other branches of scientific discovery such as insecticides, solvents, refrigerants and other products where over-enthusiastic application has led to untoward effects and public rejection. From that time on, the vastly better educated public strongly feels a right to know, discuss, understand and, where possible, participate in decisions as to where R&D should go and how it should be controlled in the interest of all.

This has spawned a realization of the social and political importance of ethical considerations in matters ranging from the release of genetically engineered organisms, embryo research, gene therapy and human genome research to the use of laboratory animals in medical research and even to the consideration as to whether a different set of more stringent rules should be applied to particular groups of animals such as domestic animals or primates.

Today, such highly emotive subjects are not only matters for careful consideration by scientists, policy makers and the scientific press, but have also become the object of sensational and often inaccurate presentation in the popular news media. This does not help to inform a public eager to understand and form opinions on matters germane to their daily lives.

FINAL COMMENT

With instantaneous communications and easy international travel, the world has become a smaller and more interdependent place, and many of the phenomena noted above will be found to be true for most of the more developed regions. The scientist is often the ambassador of closer political relations and the European scientist has helped to bring aid and education to developing countries.

The pursuit of science is a dynamic activity and science in Western Europe is no exception. The region as a whole is in evolution towards greater unity, while at the same time preserving individual cultures both in approaches to science policy and in the arts. This should be seen as a great opportunity to further develop the means to strengthen scientific ties whilst unlocking hidden talents in our less favoured areas and enlarging their potential to participate in European scientific progress.

SAM J. LLOYD is a consultant to the European Commission on research reactor management and is responsible for evaluating the EURATOM Joint Research Centre's eight research institutes using peer groups of high-level scientists and managers. He is also a consultant to a number of other organizations.

After serving in the British Royal Signals, Mr Lloyd joined AERE Harwell as an Experimental Officer in the Metallurgy Division. He was later sent to Mol in Belgium in charge of a team engaged in irradiation damage experiments on materials for gas-cooled reactors. Mr Lloyd spent four years in charge of the Irradiations Department at the Petten Establishment of EURATOM's Joint Research Centre (JRC) and then set up a small 'think tank' to develop the Establishment's new programmes. Subsequently he took over the Materials Research Laboratories and was also adviser on publications to the JRC's S&T secretariat.

In 1982 Mr Lloyd went to the JRC Headquarters in Brussels and in 1984 was appointed personal assistant to its Director-General. From 1988 till his retirement four years later he was responsible for the secretariat of the JRC's Board of Governors.

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CENTRAL AND EASTERN EUROPE

Blagovest Sendov

In order to consider the status of science in Central and Eastern Europe today and to try to assess future prospects, we have to know and understand the historical importance of the changes taking place in these countries following the collapse of the totalitarian regimes. The former Socialist countries in this region all had their specific characteristics but also shared many similar problems, since they had been obliged to follow the same pattern of development for many years. One of the features of this pattern was the organization and development of science.

The entire political, economic and cultural life in the so-called 'Socialist camp' was dominated by Communist ideology, an ideology which claimed to be the first in human history to build a society based on scientific theory. Because of this, science under the Communist regimes had a special status.

It is common today to deny and reject everything done by these regimes, but the successful transition from totalitarianism to democracy requires something more than that. It would be unreasonable to deny a number of accomplishments in social and scientific life. In Table 1 the number of personnel engaged in scientific research and development (R&D) is presented (UNESCO, 1992). This number steadily rose until 1989 in all countries excepr Hungary and Poland where it started to decrease after 1980. This may be explained by the relatively greater freedom for scientists from these countries to work abroad, and the economic and political situation prevailing there during the 1980s.

At the beginning of the changes in Central and Eastern Europe, the prestigious scientific journal *Nature* (1990) published a series of articles under the title 'Reforming Stalin's academies', one of which stated: 'One of the most obvious relics of Stalinism is the continued survival in Eastern Europe of academies of sciences whose purposes have never been fulfilled. This is the time for changing them.' To change the academies in these countries is a key issue, because of their scientific potential and the importance of science and scientists for the future of an open market economy and democratic development.

The changes in Central and Eastern Europe started and followed as a 'domino' process in a very short period of time with the downfall of Communist domination, but they by no means ended there. Moreover, it is entirely possible that yet another totalitarian regime may take shape over the ruins of the fallen one if the democratization process is not coupled with economic improvement. In the September 1992 report of the Directorate for Science and Policy Programs of the American Association for the Advancement of Science it states:

'Many of the scientists we met in Eastern Europe fear that, in the short run, they may face a succession of unstable governments and that, in the long run, social discontent may come to provide a basis for a new form of authoritarian rule. In the meantime, they argue, the current political situation, in which a multiplicity of parties vie with each other in terms of the maximum of promises for the least cost, is not good for science, since research is a

TABLE 1
NUMBER OF PERSONNEL ENGAGED IN R&D

Country	1970	1975	1980	1985	1987	1989
Bulgaria	46 633	60 939	72 335	90 308	96 471	–
Former Czechoslovakia	137 667	149 011	171 789	180 439	–	185 492
Former GDR	–	158 573	191 429	191 262	–	195 073
Hungary	50 749	60 604	62 866	48 745	–	42 276
Poland	196 200	299 000	240 000	181 000	–	–
Romania	46 382	62 918	–	–	167 049	169 964
Former Yugoslavia	36 467	42 524	53 699	68 591	–	78 704

Source: UNESCO *Statistical Yearbook*, 1992.

low priority for the majority of the population.' (Cave and Frankel, 1992, p. 22).

Transition from totalitarian to democratic civic society will be a long process. The political forces involved in that process usually concentrate on the creation of some new legal system and on the replacement of the old centralized economy by a market economy based on private property. These two reforms are certainly crucial, yet real democracy will not prove possible without institutions which study and interpret facts so as to promote more effective and responsible participation of people in the political process. Such institutions are the academies of science and the universities.

SCIENTIFIC STRUCTURES

The Socialist countries each adopted the tripartite Soviet system for scientific organizations. The academies of science through their institutes conducted basic research, the universities concentrated mostly on teaching with some basic research, and the research institutes of industry and agriculture (attached to the respective ministries) took responsibility for applied research.

Academies of science

During the Socialist period, all academies of science in Central and Eastern Europe were structured after the model of the Soviet Academy of Sciences and shared many common features, the most important being:

The academies of science were the supreme scientific bodies of the respective countries. This supremacy gave these academies a good deal of power and financial support from the government. In some respects this was at the expense of weakening research in the universities.

The academies in the Socialist countries had some governmental functions close to those of a ministry of science but, at the same time, they represented the scientific community in the country within the international non-governmental organizations. For example, in the most prestigious non-governmental international scientific body ICSU (the International Council of Scientific Unions) the countries of Central and Eastern Europe were (and still are) represented through their academies (ICSU, 1993).

The academies of science consisted in fact of two parts: a corporate part – an exclusive corporation of scientists as in the Western-type academies; and an institutional part – a large group of research units funded by the government.

The academies of science usually represented between 8% and 12% of the national research potential in quantitative terms. But in qualitative terms it was much more. For example, in 1988 about 12% of Bulgarian scholars and researchers were employed by the Bulgarian Academy of Sciences, while 52% of the Bulgaria-derived scientific publications in foreign international journals were written by its associates.

The impact of academies from Eastern and Central Europe on the scientific publications of their respective countries during the period of change is demonstrated by the proportion of publications by scientists working in the academy out of the total number of publications from each country (Table 2).

The development of the academies was not free from internal contradictions either. The activities of research institutes within the academies concealed and in effect diminished the role of academy members as a group of independent and highly capable scholars and public figures.

Universities

It is important to remember that university scientific research in all countries of Central and Eastern Europe

TABLE 2
PERCENTAGE OF THE PUBLICATIONS IN EACH COUNTRY WRITTEN BY ACADEMY STAFF

	1988 (%)	1989 (%)	1990 (%)	1991 (%)
Bulgaria	64.2	65.1	60.9	59.4
Czechoslovakia	41.4	39.1	40.0	39.8
Poland	22.1	21.2	23.4	23.5
Hungary	29.0	33.1	31.1	31.5

Source: *Science Citation Index* of the Institute for Scientific Information (ISI), courtesy of Dr David A. Pendlebury.

shared one and the same intellectual tradition with Western Europe before the Second World War. Before the socialist model of the academy was adopted, the most powerful research groups and research potential were concentrated in the universities. In Poland and Hungary, the old universities also remained important scientific centres, even under the totalitarian regime. Discussing the role of the academy in the scientific life of Poland, the President of the Polish Academy of Sciences, Academician Aleksander Gieysztor wrote:

'As in other European countries, among institutions dealing with science in my country, universities are older than learned societies and academies, they in turn are older than specialized research institutions, and those are ahead of the State Committee for Scientific Research.' (Gieysztor, 1991).

During the Socialist period, higher education was also a priority area and there were considerable quantitative accomplishments. And yet universities were still not regarded as offering serious potential for basic research. This arbitrary divorce of research from teaching was detrimental to both science and education.

One of the serious shortcomings of the former socialist academy model was its *de facto* isolation from the universities and the scientific training of young people. To overcome this defect, an experiment aimed at integrating the Bulgarian Academy of Sciences and Sofia University was launched in Bulgaria in 1972. The main idea was to overcome the separation of research from university education. This integration offered – in theory – a possibility for all scientists in the University to use the laboratories and other research facilities of the Academy and for all scientists from the Academy to teach in the University.

In October 1986, a group of 13 US scientists, engineers, research managers and economists visited Bulgaria and participated, together with Bulgarian colleagues, in a workshop organized by the Bulgarian Academy of Sciences and the US National Academy of Sciences. The following comment was made about the integration between the Academy and the University:

'The organizational integration of the Bulgarian Academy of Sciences (BAN) institutes with the relevant faculties of Sofia University is unique in Eastern Europe. While there are still significant differences in the research activities at BAN and at the University, the interchange of scientists, students and ideas has been greatly improved, and both organizations benefited considerably.' (Schweitzer, 1987).

The integration of Academy and University, although formally blessed by the Communist Party, did not meet with an enthusiastic response, since its ideas challenged certain basic tenets of the Communist regime. During the Socialist period, universities were regarded not only as important institutions of professional and scholarly training, but also as an instrument for the ideological indoctrination of future specialists. There had been occasions when talented scholars happened to disobey party instructions, and were promptly transferred to the Academy, simply to cut off their contact with students. The separation of Academy from University was no organizational mistake: it was a necessary condition for the system to function. The integration between the Bulgarian Academy of Sciences and Sofia University failed since it opposed some political postulates of socialism.

Applied research

The linking of science and practice proved an insurmountable problem for socialism. In spite of pressures exerted and money spent, no effective mechanisms were created. Many huge research institutes subordinated to various ministries came into being, but their findings were rarely put to use. The main lesson to be learned is that lack of personal interest and private initiative in applied S&T development cannot be compensated for by planning and administrative pressure, notwithstanding its strength and scope.

Now, in this period of transition from centrally planned to market economies, the institutes specializing in applied research are suffering most. Their funding from government is not justified, yet a very small fraction of these institutes are being converted into private research companies.

IDEOLOGIZATION OF SCIENCE

One of the axioms during the totalitarian regime was the mandatory division of science into true science (socialist science) and pseudo science (bourgeois science). This division was natural and very distinct in philosophy and the social sciences, where the ideological views formed both criteria and methodology. Everyone at university was obliged to pass exams in ideological disciplines based on Marxist-Leninist philosophy. Thus, in all institutions of higher education, ideological chairs were established and thousands of lecturers and professors were employed in Marxist philosophy, political economy and other ideological disciplines. Even older, established scientists were forced to go through special ideological courses in Marxist philosophy, following the socialist revolution.

When speaking about science during the totalitarian regime, we have to differentiate between the hard sciences (mathematics, physics, chemistry etc.) and the soft sciences (social and humanitarian sciences). It is true that the Communist regimes used science, and needed both hard and soft sciences for different purposes.

Soft sciences were used for establishing the scientific foundation of totalitarian regimes, and to prove their historical justification and bright future. 'The role of science in the past was to provide *post factum* justification for political decisions' (Cave and Frankel, 1992, p. 35). During this period thousands of 'scientists' were produced whose only purpose was to find 'scientific' proofs of the economic and social policy of these regimes.

The hard sciences were more independent, but not always so. Action was taken against certain scientific theories based on ideological motives, which badly hindered the development of natural sciences in the Socialist countries. Genetic theory and cybernetics were labelled pseudo sciences, and this was the most striking example of ideological interference. The fight against genetic theory was so brutal that it actually led to the death of leading biologists in the Communist countries. The fight against cybernetics and computers was also very active and led to serious delay in the development of computer technology.

Ideological control over scientists was very severe. All promotions in a scientific career had to be approved at some party level. As we say, all scientists were in the *nomenklatura*. There was no absolute ban on non-party members in science, but party membership made the life of a scientist easier. No more than 10% of all citizens were party members yet, in Bulgaria for instance, almost 80% of the full members of the Academy were party members.

It is interesting to note that whilst the Academy was the most typical totalitarian scientific organization, the scientists in the Academy were extremely free thinking and democratically oriented, as the President of the Polish Academy of Sciences explains:

'Even in the era of omnipotence of the Communist Party in social life, the composition of the Academy was to a rather smaller degree politically oriented than happened in some higher schools. With exceptions, mainly in the early times of its existence, the Academy remained a representative body of experts, appointed by experts. With the change of political conditions, our Academy, like the Hungarian one, does not have to revise its composition today.' (Gieysztor, 1991).

As a reaction to the ideologization of science during the Communist regimes, another development called 'decommunization' is now becoming an issue. In October 1991, the Federal Assembly of Czechoslovakia passed a law stipulating that anyone who had held certain positions in the Communist Party between 1949 and 1989 was banned for five years from holding government administrative posts. In Hungary, all universities had established committees that would evaluate the political credentials of the heads of all university departments. The Polish parliament also passed a number of bills for decommunization. The most far-reaching bill of this kind, specially designed for 'decommunization of science in Bulgaria' was voted in in December 1992 by the Bulgarian parliament. According to this bill, all scientists who had held positions in science administration which had been approved at the highest Communist Party level (such as rectors, presidents and vice-presidents of the Academy and others) were banned for five years from holding administrative posts in science, including leadership of the smallest scientific units, and from participating in scientific councils confirming scientific degrees. This bill is automatic and does not allow a case-by-case examination of the personal guilt of the scientists involved (around 4 000 in number).

Opponents of the laws for decommunization and human rights activists acknowledge that those guilty of real crimes should be punished. But by condemning people on the basis of association rather than on actions, the laws set a dangerous precedent. There is a lack of due procedure for those who feel they have been wrongly accused, and possibilities for abuse abound. All this increases tensions in the post-Socialist countries in addition to all the other difficulties.

BRAIN DRAIN

In the preface to the report on brain drain issues in Europe, published by the UNESCO Regional Office for Science and Technology for Europe, the following statement can be found:

'The intellectual and cultural migration that is happening now in Central and Eastern European countries during their transition to a market economy could be causing a serious loss of potential in these countries, and in Europe as a whole. It should be noted that the "brain drain" is a multifaceted process, which takes place even in Western countries, and sometimes provokes serious problems for scientific research, as well as for cultural developments.' (Angell and Kouzminov, 1991).

The brain drain in Central and Eastern Europe proceeds at two levels: the emigration of scientists to other countries and the re-orientation of promising young scientists to careers outside science. The main causes of both are low salaries, poor research funding and the deteriorating infrastructure of science.

It is not possible – and indeed may not be necessary – to fight the brain drain from the post-Socialist countries. Many talented young and not so young scientists from these countries find good conditions in which to continue their research. The main problem is now to find the mechanisms to diminish the trend. One important instrument is scientific collaboration with Western partners and financial support for joint projects performed without the need for moving scientists outside their countries for extended periods.

PROSPECTS FOR THE FUTURE

The difficult situation that science and scientists in the emerging democracies in Central and Eastern Europe find themselves in can be considered not only as a period of crisis, but more importantly as a time of great opportunity. ICSU formulated its rationale for organizing a special conference to discuss this issue as follows:

'Science, in terms of manpower and infrastructure, is vital for rebuilding democratic Eastern Europe as it is required for renovation of industry, agriculture, education and culture; for implementing new environmentally sound technologies; for the elimination and prevention of environmental problems; for participation in international cooperative scientific programmes including North-South development cooperation; and for creating the conditions necessary for economic innovation in general.'

Parliaments and governments in the region have to recognize the potential of science for the economy and the future status of these countries. From the other side, scientists have to appreciate the situation and to help with the evaluation and the necessary restructuring of scientific organizations. The international scientific community has already demonstrated its willingness to help.

Restructuring

It is evident that in the course of democratization and the shift to a market economy, the academies of science in the emerging democracies will have to reshape. Some of these academies may immediately turn to the Western European model and separate the corporate from the institutional part. The institutes may become self-sustained or join a university. This is one solution which will suit those academies in which the corporate part is more discredited and weak.

In the academies with a long tradition and a strong corporate body, the changes will be in the direction of adjustment to the new economic and political situation, without an immediate change of model. A policy of preserving existing scientific potential, which will be needed for building competitive industry in the future, is crucial.

Financing

The general trend in Central and Eastern Europe has been the reduction in government funding for research as a result of economic difficulties. For example, in Bulgaria expenditure on science expressed as a function of GNP for three consecutive years was 1989: 1.09%, 1990: 0.78%, 1991: 0.47%.

The Western system of funding projects in basic research, using peer reviews, was started in several countries of Central and Eastern Europe some years before the fall of the totalitarian regimes. What is needed now is the establishment of governmental agencies of the National Science Foundation type, in order to finance scientific projects on a strongly competitive basis. This is the instrument to bring basic research back to the universities.

To tap the growing potential of private business in the support of science, it is vital to bring in special legislation for tax exemption in supporting scientific activities.

Academician **BLAGOVEST SENDOV** was formerly President of the Bulgarian Academy of Sciences and Director of its Centre for Informatics and Computer Technology. He was previously Rector of Sofia University and has served as Vice-President of the Intergovernmental Informatics Programme of UNESCO from 1986 to 1990. He is the author of several publications in the field of approximation theory, mathematical modelling in biology, and computer sciences.

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RUSSIA

Sergei Kapitza

The momentous changes that have occurred during the last few years and are still going on in Eastern Europe and the former Soviet Union are destined to have long-lasting effects on the political, economic and social conditions of a great part of the world. At a time when even the borders of these countries are evolving, it is difficult to expect due attention to be given to the present state and future development of science. However, if we have a longer and perhaps a more detached view of what is happening, then the future of science can be seen to be intimately connected with these changes. Societal developments in the short term serve to determine the present state and conditions for science and technology, but in a more distant perspective science itself is to become a crucial factor in the new liberal and democratic world-to-be.

If we look at the present conditions for Russian science, the significant feature is that most of the state support has gone. Gone not only because of the major economic crisis that has hit the country, but because Russia is going through a profound reconsideration of the place science is to have within it. Under the *ancien régime* the hard sciences were to a great extent subservient to the military effort, an effort that over the decades had contributed to the build-up of a fearful system of armaments. From nuclear weapons to rockets and guided missiles, ships and planes, guns and tanks, science had determined the high level and sophistication of the armed forces.

It must be admitted that those in charge of the large military-oriented programmes were generous in their support of fundamental science. There was an understanding of the overall significance of scientific culture, of the general background needed to sustain a level of development for a global power operating on a world scale. But during the last 20 years there has been a systematic decline in support for what is called 'Big Science'. For example, not a single large accelerator or research reactor was commissioned, in spite of promised support. The once-ambitious space programme has also lost much of its impetus. The large fleet of Russian oceanographic research ships is now stranded because of lack of funds. With the collapse of the Soviet state, the demise of communism as it was practised, and a marked fall in industrial production due to a deep economic crisis, hard science has simply lost most of its bearings and support.

On the other hand, the soft sciences are in even greater disarray, for the whole system of ideas that they were serving has gone. Today, literally tens of thousands of teachers of Marxist philosophy, the history of the Communist Party and of political economy have lost their jobs and in many cases a meaningful existence, since the very substance of their studies has disappeared, indicating the scale of the crisis of ideology. In other words Russian science has to demilitarize the hard sciences and de-ideologize the soft.

In the former Soviet Union the main body that, to a remarkable extent, determined the policy and high status of science was the Academy of Sciences. Among its members were many scientists of great distinction. Unfortunately, during the years of decay high standards were often sacrificed for the sake of political expediency. A marked decrease in the standards of the Academy occurred when the newly formed Academy of the Russian Federation merged with the Academy of Sciences of the former USSR. It so happens that the Academy, the establishment of Soviet science, has tended to associate itself with those who were opposed to change, be it the *perestroika* of Gorbachev or the reforms of Yeltsin. The conservative policies of the scientific establishment have led to a deep split in the academic community, culminating in the organization of a number of alternative societies of scientists, new academies and even universities. Of these one should note the Academy for Natural Sciences, which has striven to unite scientists from a broad spectrum of institutions, including the universities.

At present, the funding for science has been cut. It is reported that funding of the Russian Academy of Sciences, with its huge network of institutes, libraries, observatories and publishing houses, has been decreased by a factor of three to five. Due to such drastic drops in funding and the opening up of new opportunities in business and entrepreneurial activities, many are now leaving science. This is mainly happening with the younger and more dynamic generation, and probably a quarter of all scientists may thus leave science, a quarter may leave the country and of those left half could retire; in the end it would not be surprising if the country were to be left with only 20-25% of all scientists now actively engaged in research. This stage has not yet been reached, but one has to keep in mind such a trend for the future.

The changes are not only imminent, but even necessary, however painful and drastic they may be. Science in the USSR was overstaffed and top heavy. For years it tried to develop as a self-contained entity, to a great extent isolated from world science, and this is another reason for change now the country has opened up. It is under these conditions that we should attempt to formulate the national science policy of Russia, to define its new priorities.

THE NEED FOR FUNDAMENTAL SCIENCE

To understand better the modern demands and challenges we should look at the complex interconnections between modern science and society and the economy. In the first place let us consider fundamental science, science pursued for the sake of knowledge. Basic science is motivated by the deep-seated need to understand and interpret the world around us and that of humankind itself. On the other hand applied research is pursued because of its usefulness. Today the profound connections between fundamental science and culture are generally recognized, although these tenuous ties are strained by growing antiscientific and anti-intellectual forces. The applied sciences, intimately linked with industry, have a direct effect on technology and economic development.

In terms of investment, fundamental science, applied research and development (R&D) and industry can be represented by the ratio 1:10:100. However, if we were to think in terms of the time it takes to develop a set of concepts in fundamental science and then a trend in applied research, and finally to carry the impact into industry, the reverse relationship applies (i.e. 100:10:1), for it may take decades, perhaps even 100 years, to develop a tradition in fundamental science or build up a university, or 10 years to develop a field of applied research, whilst an industrial enterprise can switch over to a new product or model in a matter of a year. For example, the fundamental discoveries in quantum mechanics led within a generation or two to the invention of the transistor and then the laser. A century before, the theory of electromagnetism provided the background for the development of the electrical industry and later radio, television, radar and modern communications. Today, perhaps on a shorter timescale, we are witnessing the remarkable impact of discoveries in modern genetics and molecular biology on the practice of medicine and agriculture and on progress in evolutionary and environmental studies. Discoveries in astronomy and cosmology are being made possible by new technology, especially by space technology provided by the aerospace industry. These novel methods and facilities are used for observing the Earth and have resulted in a virtually new way of looking at planetary phenomena. Thus, fundamental sciences, in close cooperation with modern technology, have a continuous and very profound effect on our understanding of the world, on our well-being and on our civilization.

As has been indicated, fundamental science has a long development timescale. The long-term factors that affect the development of fundamental science can be seen in that only now, some 40 years after its defeat in the Second World War, has Germany regained its position in the field of science, a tradition that to a great extent was destroyed during the years of Nazi rule.

Today, the impact of the newly emerging countries of Asia and the Pacific on industry and even on applied sciences is far greater than their contribution to fundamental research. The difficulties in establishing a regional or national tradition in basic science has even led to the notion that such attempts ought not to be made, since fundamental research is today pursued as a global intellectual enterprise. In so far as this is true, it does not mean that in a developed scientific community fundamental research should not be pursued, for it is part and parcel of our modern culture and directly contributes to higher education as long as it is practised on a national basis. It is for this reason that any discontinuity or serious stoppage in the development of science in Russia may have long-term effects and should be of immediate concern both for the scientific community and the country as a whole.

The current economic reforms in Russia are affecting industry in a major way, and to a great extent affecting applied research as well. The law of supply and demand can and should determine the new pattern of development and here we may expect rapid and profound changes:

changes that will also affect the huge military-industrial complex of the former Soviet Union. To a great extent the transformation to a market economy is a change from the military-oriented command economy of our recent past. Thus military defeat in the Cold War, a war never fought outright but whose economic consequences are now with us, is dictating the reforms.

It is in this state of turmoil that fundamental science has become lost. In the first place one cannot and should not carry out fundamental science according to direct market forces. However clear the responsibilities of science and however diligent scientists are in the way they conduct their business, no short-term bookkeeping and direct monetary control can really estimate the value of the immediate output of fundamental research. If one wants to calculate the efficiency of fundamental science, it has to be done on a long-term basis, of decades at least. It is well known that the balance is much in favour of science, but this happens not because it was designed to work that way, but because the power of knowledge has an immense multiplying factor. If an invention, the result of applied science, of R&D, leads to gains in percentage or even in an order of magnitude, we see how the discoveries of fundamental science open new fields of human endeavour. That is why basic fundamental science should be supported by the state and by society; and the public should be fully aware of this. The level and accomplishments of basic science should primarily be assessed by the world scientific community and society at large and seen as a major part of modern culture.

The main way in which fundamental science has such a profound effect on our civilization is due to the extent to which the coming generation is exposed to the ideas and concepts of new science. This, as one may see, is an utmost priority for science in the service of society. It should be seen as the most significant part of the new long-term contract between science and society that now has to be negotiated and pursued as a result of the new set of social conditions in the countries of the former Soviet Union and its constituent states. Previously serving the grandeur of the country, as expressed in large and seemingly impressive projects or in sheer military might, science in Russia now has to redefine its mission.

What, then, should we do with Russian science? First it should be integrated to a much greater extent with the universities, with training the next generation of scientists and engineers, doctors and lawyers, teachers and statesmen. It is this new generation that is to be the real instrument of reform, our main hope for the future. The continuity of teaching, and of training, of this next generation should have the highest priority, both for science and the country.

NEW DEPARTURES

At times of decisive transformation of society, when there is a challenge to the existing system, new educational institutions tend to be founded. During the French Revolution the *Grandes Ecoles* were established. After the Russian Revolution, and under the pressure of industrialization in the 1930s, the present system of technical institutes was set up, institutionalizing to a great extent the separation of research and teaching. After the Second World War, with the post-war demands for high technology and armaments, the now-prestigious Moscow Institute for Physics and Technology was founded. Its development was due to a suggestion by leading Russian scientists and it received the full support of the party and the government. It became a very successful, although singular, example of the uniting of teaching and research, with special emphasis on educating future scientists and engineers with a thorough course of physics and mathematics, taught by the best brains available. Today this experience can and should be used for new departures in third-level education. For example, an important development has been the setting up of teaching departments at a number of science centres around Moscow to expand the graduate training capacity of these specialized scientific institutes.

More than ever, Russia has to sustain and develop its tradition of higher learning. Apart from oil and gas, our brains are arguably our main asset. Of the things that were great and good in the Soviet system we should certainly count the long-standing traditions of education, a respect for knowledge and the status of science. Russia must now learn how to employ this major asset gainfully. It is here that we can hope for ties to be set up between the newly emerging entrepreneurial class and science and technology. The Communist regime did not really manage properly to develop and employ the intellectual potential of society as the most dynamic and progressive factor in the modern world. Instead, the Marxist idea of the supremacy of the working class interpreted in a dogmatic way, subservient to the political interests of the ruling party, contributed to the collapse of the Soviet state. Probably in no field was this so evident as with computers and information technology.

Unfortunately these positive attitudes towards science and technology are under great pressure. A successful profiteer may become a millionaire in a day, then squander his money in a night. A taxi driver earns 10 times more than a doctor or a university professor. Administrators, even of the Academy of Sciences, are much better off than scientists themselves. Science as a cultural phenomenon, and science and technology news, have vanished from our newspapers and television, our public mind. Antiscientific trends are rampant, astrologers and quack doctors flourish. To a great extent these are symptoms of the profound crisis through which the country is passing (see *Scientific American*, August 1991). On the other hand, it certainly reflects a new and deep-seated resentment towards science. Haven't the propagators of Marxism said time and again that this is the only true scientific system of ideas, on which to build a brave new world? Haven't the scientists, especially the physicists, promised bliss from nuclear energy, culminating in Chernobyl? Haven't other less prestigious projects failed to deliver, be it the imminent prospect of fusion energy or the expected arrival of high-temperature superconductor technology? How should we now account for the success of space exploration, after the initial spectaculars? And what are we to do with the mess in our environment?

Here it should be said that Chernobyl was more the result of the social and psychological unpreparedness of our industry and society to enter the nuclear age than that of defective technology, and that the early promise of thermonuclear energy and room-temperature superconductors was made, or rather implied, by the world scientific community. We should admit that these questions are to be addressed not only to Soviet and Russian science, but to the broader global constituency of scientists: issues and promises that sooner or later will have to be resolved. For in a certain sense the crisis in Russian science and even in the former Soviet Union in general is a phenomenon that reflects in an amplified way some of the critical problems of the world as a whole. This point of view is not fully appreciated and even less pursued; it deserves to be taken more seriously.

INTEGRATION WITH WORLD SCIENCE

The next priority of Russian science policy should be that of integrating our science into world science. In applied science this will happen in due course as our industry becomes gradually integrated into the world economy. One can only hope that in this process Russia will cease to be an exporter of commodities and arms, and will manage to develop its high-technology and knowledge-based industries for more benign purposes.

The integration of Russian fundamental science into world science cannot happen immediately, for the separatist traditions are deep-seated, having been cultivated for decades. Here again our foremost priority should be to provide opportunities for the younger generation to be open to world science as soon as possible. At the beginning of Gorbachev's era some seven years ago there were at least 25 000 students from the People's Republic of China studying in the USA. Discussing this matter during a dinner in Washington I pointed out these figures to our ambassador and asked him how many Soviet students and scientists were currently in the USA. Less than 100 came the answer. This message was delivered to Gorbachev. His action was immediate and supportive, but hardly anything happened. At present there are reportedly 40 000 Chinese students and still only a few thousand Russians.

Today much is spoken about the brain drain. In spite of all the surrounding publicity the figures are not as yet alarming. The outflow of scientists should partly be seen as a way of normalizing the connections and ties between Russian science and the world at large, for we do have to compensate for the decades of self-imposed isolation. In the international exchange statistics we can see the trends and development in Russian science (Table 1). Hopefully with the stabilization of the political situation a redefinition of priorities will occur, and we shall see the return of scientists to the country.

TABLE 1
EXCHANGES AND TRAVEL CARRIED OUT BY SCIENTISTS OF THE RUSSIAN ACADEMY OF SCIENCES

Purpose of travel	1991	1992
Attend conferences	6 956	5 058
Exchange collaboration	1 506	628
By invitation	8 451	7 357
Expeditions	329	112
Contracts (long-term visits)	467	881
Accompanying persons	1 262	1 597
Total	18 971	15 630

The figures in Table 1 were provided by the international department of the Academy. They are self-explanatory and reflect the decline of research activities, especially in fundamental science, at home. The Academy accounts for one-tenth of all scientists.

What really matters is that key members of the academic community are leaving, books on science are ceasing to be published and the continuity of research and teaching is being lost. For example, the revised volumes of the world famous *Course of Theoretical Physics* by Landau and Lifshitz have been stranded for more than two years in the publishing house of the Academy of Sciences for lack of funds. Many senior members of that remarkable school of physics have also left, and here the continuity of an internationally recognized tradition may be broken.

One can certainly have nothing against the worldwide traffic of scientists. But what is surprising is that when a football superstar is transferred from one club to another, many millions are paid, demonstrating to the world the significance and real cost of that individual. Alas, when a great professor is invited abroad, nobody ever thinks of compensating the institution that trained and nurtured for years this scientist of distinction. Can we expect in such circumstances to generate in the public mind the strong image of science, or support for the sources of such very special talent?

Today the image of science and the status of scientists need to be cultivated and developed to a much greater extent than ever before. The painful lesson of Russia has a message for many other countries, to the extent that the decline of science is being thought of by some as an imminent global phenomenon. The writer does not share these gloomy generalizations, although unfortunately scientists themselves often engage in doom mongering. In most cases this is a rather primitive exercise in modern pseudoscientific eschatology. Good as brainteasers, these messages often generate despair rather than hope, demoralize rather than help us face the real issues of the world and of our civilization.

Since the Age of Reason science has promised much. Now it seems that the day of reckoning has come and it is probably high time that the world scientific community started to show less complacency and more fortitude in assessing and defining its priorities. In developments challenging Russian science this has to be taken much more seriously than ever before. Can these new priorities be worked out by the old and conservative academic establishment, or are new leaders to emerge? To what extent can the management of science be left to scientists themselves? Can one paraphrase the old maxim that war is too important a business to leave to the generals? In no way should it be thought that the writer is for the introduction of administrative control of science (in Russia we have a good deal of very unfortunate experience in such matters), but today's critical situation does demand new ways of resolving the complex issues facing the scientific community. To what extent such decisions could be assisted by international advice is a very important question. It is probable that external authority could help to overcome the vested interests of the 'old boys' club' that up to the present, not without some success, has been running Soviet and now Russian science.

Many question the authoritarian manner in which much of Soviet science (and not only science) was governed, and want to extend the new democratic concepts to science administration. This is not an easy matter, but an issue that has to be faced and resolved in one way or another. Probably a new governmental means of administering funds, similar to the National Science Foundation (NSF) in the USA, or Germany's *Deutsche Forschungsgemeinschaft* (DFG) should be envisaged, separating advice and decision making. Of the greatest importance for such an agency would be the execution of a new scientific policy to be worked out both by the scientific community and, it is hoped, parliament. This could be expected only with the introduction of the new legislature.

HELP FROM OUTSIDE

It would be proper to mention the help and assistance being provided to Russia by the world scientific community. Much has been done to provide for the continuity and availability of scientific publications, since most library funds in Russia and the former republics have been cut off. The initiative of publishing and distributing *Nature Monthly* at a reduced price, thus opening up a significant channel of communication with world science, is very much welcomed. Grants to individual groups of scientists are of great help, as is support to centres of excellence that so need protection. Funds for travel are important, especially for young scientists. Of the assistance to Russian science coming from foundations, the support by the Soros Foundation in the USA is worthy of special mention.

These contributions are significant at a time of change and frustration, when the fragile body of science could so easily collapse. But one cannot sustain a long-term science policy by such means; some even say that this help may undermine the structure of Russian science, or rather what is left of it. In providing support for individual scientists and science projects it is very easy to upset the all-important balance between the distinct group and the host institution that provides much of the infrastructure and the intellectual tradition of a good centre of research. Of all centres of study, the universities have a more permanent nature than any other institution. Today we see how mission-oriented centres of research, centres that could even be considered to have once been centres of excellence but now to have fulfilled their purpose, have great difficulty in finding support and a socially acceptable means of existence. This is best seen with military research establishments. Finally, one has to bear in mind that only the country itself can and should really define the priorities and manage its science. The visit to the Russian Academy of Science by the new Prime Minister shortly after his appointment is a hopeful sign.

In the foreseeable future the greatest loss is likely to be experienced by experimental research, since it is more costly than purely theoretical work, the latter always having been strongly represented in the former Soviet Union. The long-term and serious lag in development of Big Science has already been mentioned. Should the state continue to support these large laboratories which now, by any standards, have lost time, staff and much of what they had to offer? On the other hand, large-scale projects need to be chosen on the basis of their significant contribution to national goals and the international community of science. Here again, new priorities have to be defined. Unfortunately the pressure of former commitments, of the vested interests of large and often still powerful groups, and the tradition of continuity, make it all the more difficult to make the right decisions and then carry them out.

Due to lack of hard currency the former obligations of Soviet science towards international institutions and learned societies and projects now taken over by Russian science are all frozen. International financial assistance and help would be most welcome to meet these payments and debts. Funds now offered for technical assistance might be allocated to international institutions for the support of research by Russian scientists and scientists of other countries that cannot at present find the means to participate at the national level.

KEEPING UP MORALE

In times of difficulty and strife moral factors become important. Probably of all the reasons for the loss of will and morale on the part of scientists, the lack of appreciation of their work and even their place in society must rank highest. The change in values now taking place in the country is having a significant effect on the attitudes of the younger generation. Anti-intellectual trends seen in media freed from censorship and responsibility towards society, coupled with expressions of rampant nationalism and antisemitism, add to the frustration and despair felt especially by the young and promising generation at the postgraduate and postdoctorate level, forcing them to leave science or the country. These issues and the public attitude of society towards science are usually not taken into account, but they are of great importance. Recently, on the initiative of the Academia Europaea, 20 prizes were granted by an international jury to young scientists of the former Soviet Union, in a move to support the next generation at a decisive time of their career. One of the real responsibilities of the senior generation and of the world community of scientists is to recognize this mood, for whilst the state of the body may be repaired by money, the spirit is much more elusive, yet is crucially instrumental for the success and future of science.

Nuclear weapons laboratories are of special concern. Perhaps it is there that some of the fundamental difficulties of converting the research branch of the military-industrial complex can best be seen. Right from the start these institutions were off limits – beyond limits in terms of money and resources and also off limits in terms of contact not only with world science, but even with the majority of their colleagues at home. Now they are open to the world – they have to redefine their priorities and find new ways of employing the very special talents of their scientists and engineers, the great resources at their command. This is no simple matter, due to the very high degree of compartmentalization of such mission-oriented research establishments. Another factor that has to be recognized is that of the high average age at these institutes, which only serves to make changes even more difficult. One may only hope that this challenge and ensuing changes will not lead to an intellectual dimension in nuclear proliferation. The sense of responsibility developed amongst the staff of scientists and engineers at these remarkable centres of research now becomes a duty with regard to global, rather than national, security in the spread of nuclear weapons.

SCIENCE IN THE INDEPENDENT STATES

The break-up of the Soviet Union into a number of independent republics, and the new policies pursued by Eastern European states, have led to new conditions for the development of science. After the euphoria of independence, when scientists in the newly independent republics were often the most vocal spokesmen for the new freedoms, many have now to face the facts of life. For example the heads of state of two former republics of the Soviet Union were professors of physics – President S. Shushkevich of Belarus and President A. Akaev of Kyrgyzstan. If support for science is low in Russia, things are often even worse in many of these newly independent countries, and much rethinking and reorganizing is needed. The initially severed professional ties with Russia are now gradually being repaired, and much has to be done to redefine the connections in the Russian-speaking world in terms of training students, granting degrees, publishing books and journals, organizing joint conferences, in other words, in support of the infrastructure of science. Science may and should become an integrating factor for these states, and here international professional organizations have a special mission. For example, the old Union of Scientific and Engineering Societies has been reconstituted as an association of such societies of the new republics of the former Soviet Union. In a similar way, the Physical Society of the Soviet Union has recently been transformed into the Euro-Asian Physical Society, following the concepts of the European Physical Society. To what extent these new international organizations will manage to unite scientists in parts of the world so divided by nationalism has yet to be seen.

Although each of these countries has problems unique to its own situation, many of them follow from the way things were organized in the USSR and copied by its former allies. Probably here the crisis of the academies is one of the common features. In Germany, for example, the former East German Academy of Sciences has been disbanded, whilst in other countries profound changes are being found necessary. The financing of science through foundations, directing funds to specific projects and individuals rather than supporting institutions, is assuming greater importance. In this case internationally available expertise becomes a significant factor in assessing research projects. The greater independence and objectivity of outside expert opinion may introduce common standards of excellence with reference to world science, lead to the development of personal and institutional ties and help identify new priorities in national science policy.

However varied the conditions in these countries are, the case of Russia is of special significance. It is here that the challenge of reform is most acute, not only because in this country the policies that must now change were pursued for 70 years, longer than anywhere else, but also due to the sheer scale and complexity of the society now in this state of great turbulence. However painful and even traumatic these changes are, we have to see them in the context of a profound social transformation, the true magnitude of which only future historians will measure.

PROFESSOR SERGEI KAPITZA was born in Cambridge, UK, in 1928 and is currently at the Institute for Physical Problems of the Russian Academy of Sciences, Moscow. He also teaches at the Moscow Institute for Physics and Technology. Trained at the Moscow Institute for Aeronautics, he has worked on hydrodynamics, magnetism, applied electrodynamics, accelerator design and nuclear physics. For 20 years Professor Kapitza presented the main Russian television programme on science, and was awarded the 1979 Kalinga Prize by UNESCO in recognition of his contribution to science popularization. He has also written five books and numerous articles on science and public matters.

THE ARAB STATES

Fakhruddin A. Daghestani

The political awakening of the Arab Region after the Second World War was accompanied by a resolve to build modern states relying on science and technology (S&T) and to cooperate among themselves to achieve a high degree of collective self-reliance and economic integration. If the management of affairs is judged by results, the Region today can be considered as an economic failure due to economic fragmentation, poor interregional trade, over-reliance on technological trade, and weakness in endogenous S&T capacity. Indicators show that in 1990 the average adult illiteracy ratio in the Arab States was 42%. Enrolment ratios at the second and third levels of education were 52% and 13% respectively, while enrolment in technical schools was only 12% of those at the second level. On the other hand, around 68% of university undergraduates are enrolled in the social sciences and humanities, leaving only 32% spread over all other fields of science. Research and development (R&D) activities are still limited, since the full-time equivalent (FTE) number of researchers is around 318 per million population while the R&D investment is around 0.75% of the 1990 gross national product (GNP). Science is a powerful instrument for accelerating development, but if science is needed to effect change in Arab society, this society has to introduce within itself the changes required to create an environment in which science can grow.

SCIENCE IN THE ARAB CULTURE

Prior to Islam, Arabs living adjacent to the Mediterranean Sea and in parts of North Africa shared the Byzantine knowledge of science and technology, but those living elsewhere enjoyed little of this knowledge. However, the situation changed with the adoption of Islam in the middle of the 7th century AD. Islam as a religion promoted the acquisition and production of knowledge about humankind and on natural phenomena through scientific inquiry, as an act of faith and for the purpose of improving living conditions. Islam introduced ethics to define people's relationships with their fellows, and the concept of the nation of Islam (*Ummah*) unifying all Muslims. Furthermore, Islam encouraged trade, free enterprise, manual skills and economic development. These factors promoted a situation that combined in a single system the following:

- the quest for scientific inquiry using inductive and deductive mental faculties (know-why);
- the acquisition and transmission of knowledge by learning and teaching (education);
- the efficient use of knowledge for the benefit of humanity (know-how);
- free trade, entrepreneurial behaviour and social security;
- a large common economic market covering the domain of the Islamic *Ummah*.

Under this system, and with an enlightened leadership with vision, Muslims were able to establish a dynamic and a varied civilization that carried the banner of science and technology and attained a powerful economy that was to last for six centuries.

Science started to lose ground in Arab society when the concept of *Ummah* weakened and the unity of knowledge in Islam suffered, creating a rift between the cultural values given to revealed knowledge and to knowledge acquired by reason. In Islam, the sources for making a judgment in social and religious affairs are the Holy Quran, the *Sunna* (sayings of the Prophet), *Ijtihad* (independent judgment based on reason), *Ijmaa'* (consensus), and *Qiyas* (analogy, inference). When the learned in society associated themselves with despotic leadership, freedom of expression was suppressed and the role of *Ijtihad* was reduced. Consequently, inductive reasoning took a marginal position in culture and the motivation for scientific inquiry dwindled.

Against this background, the Arab States became independent after the Second World War. It was at this stage that larger segments of Arab society started to demand more education. In many cases political authority responded positively to this demand. In general, the educational systems in the Arab States put more emphasis on learning facts and storing information than on developing the power of observation and analysis; therefore, the ability to absorb 'scientific method' and to use it in generating new scientific knowledge has not been enhanced. In other words, the use of inductive reasoning has not been sufficiently promoted. Since contemporary Arab culture is closely interwoven with Islam as practised today, science cannot take a prominent position in culture without a true revival that fully opens the doors to the role of *Ijtihad*, or independent judgment based on reason in matters of religion and worldly affairs.

In brief, the status of science in contemporary Arab culture can be summarized as follows:

- learning and teaching is rapidly gaining social importance;
- the value of 'scientific thinking', or inductive reasoning, is gradually gaining recognition by larger segments of society which associate science with progress;
- small segments of society associate science with foreign domination and regard it as a cultural invasion;
- many areas of science and technology are linked with manual labour, but this labour is still not socially acceptable in several strata of Arab society.

Unless this picture changes rapidly, it will perhaps take two generations or so for science to achieve a firm position in Arab society.

INPUTS TO ECONOMIC GROWTH

Economic growth occurs as a result of two main types of input: *quantitative*, such as labour, capital and land, and *qualitative*, provided by scientific and technological hardware and software embodied in the skills of human resources and organizations. It is believed that the major part (60-70%) of economic growth achieved by the industrial market economies is due to the generation and application of S&T knowledge in the production of goods and services. On the other hand, economic growth in the Arab States has been driven more by quantitative inputs than by S&T. Economic growth has been achieved by most Arab States during the past four decades, but this growth has been due to income generated from the export of natural resources or income borrowed from external sources. A high standard of living may prevail in oil-rich countries, but others are already facing economic depression, unemployment, social unrest and the pinch of external debt service. In all cases, the Arab States have relied heavily on technology trade, neglecting to a large extent real technology transfer in the sense of developing endogenous S&T know-how compatible with the needs of sustainable development.

These faults cannot be totally blamed on decision makers, since society as a whole is not yet driven by a 'science culture', without which society as a whole cannot be motivated to do the right things correctly, even when dictated by government authority. With this background, one can perhaps understand the reasons underlying the poor state of the Arab economy and science as described by the indicators given in this chapter.

Land and population

The Arab States occupy a strategic location covering 13.67 million km^2 (145% of the area of USA), of which 72.7% is in Africa and 27.3% in the Middle East, with the Arab Gulf countries comprising 18.1% of the total area. Size of territory varies greatly, from as little as 680 km^2 for Bahrain to as large as 2.5 million km^2 for Sudan. In addition to Sudan, the countries of Algeria, Saudi Arabia, Libya, Mauritania and Egypt each have an area exceeding 1 million km^2. Around 96% of the Region is arid and semi-arid, while only 4% is arable and cultivated, and only 0.8% is irrigated land. Arid and semi-arid land makes up 95.6% of the total area of the African Arab States, 99.5% of land belonging to members of the Gulf Cooperation Council (GCC) and 89.3% of the remaining Middle Eastern countries. The percentage of arable and cultivated land is between 20% and 30% in Lebanon, Morocco, Syria, Tunisia and Palestine (West Bank and Gaza Strip) but, with the exception of Iraq (12.5%) this ratio is less than 5% in the rest of the States, which have a combined area of 90.9% of the total area of all Arab States. The percentage of irrigated land is less than 0.2% in Algeria, Kuwait, Libya, Mauritania, Oman, Saudi Arabia, Somalia and the UAE and around 0.6% in Jordan and Yemen. Higher values are found in Lebanon (8.4%), Iraq (5.8%), Syria (3.2%) and Egypt (2.6%). These indicators point to the fact that the Arab States have to make a special effort to develop their S&T capacity in order to use increasing parts of the 13.12 million km^2 of arid and semi-arid land for sufficient food production to overcome the food deficit through the adoption of appropriate technologies, and to develop efficient water management techniques so as to optimize water usage and further explore ground-water resources.

Several Arab States are rich in mineral resources, some of which are already exploited. The proven and recoverable oil and gas reserves in the Arab States are 600 billion barrels and 24 900 billion m^3 respectively, constituting 60.6% of world oil reserves and 22% of world gas reserves. These percentage shares are very high when compared to OECD reserves, which amount to 5.9% for oil and 13.8% for gas. This calls for the development of S&T capacities to maximize income from oil and gas resources by developing competence in petrochemical and related manufacturing industries, to increase the degree of national involvement in oil and gas exploration, and management of these resources, and to further explore mineral resources as yet undiscovered.

In 1990, the total population of the Arab States reached 221.8 million, the result of an average annual increase of 3.1% during the 1980s. This increase is high compared to 0.6% for the industrialized countries and 1.7% for the world. The population is rather young: 62.5% is in the age group 0-24 years and 43.5% in the age group 0-14. These figures are high compared to the figures 36.8% and 21.8% respectively for the two groups in the industrialized countries. Egypt, Algeria, Morocco and Sudan each had populations greater than 25 million in 1990. The GCC countries have a small population and labour force, compensated for by expatriates, who constitute around 25% of the population in Saudi Arabia and around 70% in Kuwait, the UAE and Qatar. The large percentage of young people in the Arab States implies that high expenditure is required to cope with the increasing demand for education at all levels, and that the number entering the labour market every year is continually increasing beyond the absorption capacity of economic activities.

Income, industry and agriculture

There is great diversity among the Arab States in terms of GNP per capita income, ranging in 1990 from US$120 in Somalia to US$19 860 in the UAE. Five States, namely Djibouti, Egypt, Mauritania, Somalia and Sudan, with 39.4% of the total population, had a per capita income below the poverty line of US$630. On the other hand, Kuwait, Qatar and the UAE, with 1.9% of the total population, are among the high-income economies with a per capita income in excess of US$15 800. Other Arab States fall between these extremes. In 1990, the total gross domestic product (GDP) of the Arab States reached US$382 billion, of which 39.5% was generated by the GCC countries. This total GDP is equivalent to 77% of that for Spain (US$492 billion) and 35% of that for Italy (US$1 091 billion).

Depending mainly on quantitative inputs for economic growth does not make countries rich; this is evident from the fact that the GDP of the six GCC countries was US$151 billion, which is less than that for relatively small countries such as Austria (US$157 billion) and Sweden (US$228 billion). While the six GCC countries rely on natural resources, Austria and Sweden rely on S&T for economic growth. The poorer 14 Arab States are under the heavy burden of external debt. In 1990, the external debt reached US$150 billion, which is equivalent to 93% of their total GDP. Their debt service reached 39.6% of all their exports, leaving very little hard currency for further economic development. The constant reliance of the Arab States on quantitative inputs for economic growth and the weakness of their science and technology capacity have led to the present state of affairs.

In 1990, the average share of industry in the total GDP of the Arab States was 41.5%, but the average share of manufacturing production was only 11.8%. This means that the share of manufacturing was only 28% of industrial production, while the rest was mainly due to the recovery of resources such as oil and gas. This is evident from the fact that the GDP share of industry in the eight oil-exporting countries was over 42% while manufacturing was 10% or less. Total manufacturing production in all Arab States reached US$44.5 billion, but this production is less than that of our two European examples Austria (US$45.5 billion) and Sweden (US$54.7 billion). The weakness of this sector in the Arab States also implies deficiencies in endogenous S&T capability. A further proof of this lies in the fact that 81.5% of all Arab exports are raw materials and other primary commodities (oil and minerals 72.7%), while at the same time 73% of all imports are manufactured goods.

Total agricultural production in the Arab States, employing 38% of the labour force, amounted to US$45 billion in 1990, 11.8% of the GDP. This production figure is less than that of France (US$48 billion) which employs only 4% of its labour force in agriculture. All the Arab States are net importers of food; the average food import dependency ratio increased from 35.3% in 1981 to 38.1% in 1989, while the import of cereals increased from around 35 million tonnes in 1986 to around 40 million tonnes in 1989.

ILLITERACY AND SECOND-LEVEL EDUCATION

Illiteracy

The adult illiteracy rate in the Arab States taken as a whole was reduced from 66% in 1970 to 47% in 1985, and 42% in 1990, at an average annual rate of reduction of 2.3%. This means that in 1990 there were around 60 million illiterate adults, of which 39 million (i.e. 65% of the total) were in Egypt, Sudan, Morocco and Algeria. If past reduction rates prevail after 1990, it will take 60 more years to reach the desirable target of a 10% illiteracy rate among the Arab population. Since the illiteracy rate among women is twice that of men, and since the rate is higher in rural areas, special efforts must be made to reduce illiteracy among these sectors of society.

The illiteracy rate is less than 23% only in Jordan, Palestine, Lebanon and Bahrain; on the other hand, it is above 60% in Djibouti, Somalia, Sudan and Yemen. In Algeria, Egypt and Morocco the figure is above the regional average of 42%, whereas values for the remaining countries are in the range 27-38%. Jordan, Palestine, Saudi Arabia and Bahrain had a good record in illiteracy reduction during 1970-90 (see Table 1). It is expected that the target of 10% illiteracy can be reached by Jordan, Palestine and Bahrain by the year 2004, and perhaps a few years later by Kuwait and Saudi Arabia.

Reduction of illiteracy, especially among women, has to be among the top priorities of development efforts. Countries with high illiteracy rates cannot expect to benefit from the fruits of S&T knowledge.

Enrolment ratios and science at the second level

One of the reasons for the low illiteracy reduction rate is the relatively low level of enrolment at the first level of education. Although the ratio increased in the Arab States from 62.5% in 1970 to 84.2% in 1989, with an average annual increase of 1.6%, it will still take a few more years to reach the desirable ratio of 95%.

The average enrolment ratio by age group in second-level education in the Arab States increased from 38% to 51.5% during 1980-89, at an average annual rate of 2.26%. This means that if the rate is maintained, the enrolment ratio will reach 90% by the year 2014. Countries having very low ratios, i.e. 20% or less, are Djibouti, Mauritania, Somalia, Sudan and Yemen (see Table 1). Those above the 51.5% average are Algeria, Bahrain, Egypt, Jordan, Kuwait, Lebanon, Qatar, Syria and the UAE.

Enrolment in technical schools at the second level is of particular importance to science and to economic development. Only a small proportion of students at this level are enrolled in technical schools in the Arab countries. In 1989, the ratio was only around 12%, an increase from 10.7% in 1980, but low indeed when compared to the 37% of the industrialized countries. If the rate of increase of 1.28% is maintained beyond 1989, then the enrolment ratio will reach 37% only in the year 2075. The extent of the low enrolment in technical schools at the second level can perhaps be further appreciated when we realize that in 1989 the average enrolment ratio by age group was only 6.2% in the Arab States compared to 34.1% in the industrialized countries.

The ratio of students in technical fields at the second level is above the stated average only in Egypt (21.8%), Bahrain (18%), Iraq (13.7%), Tunisia (13.3%), and perhaps Lebanon, but the values are very low in the UAE (0.8%), Saudi Arabia (1.9%), Qatar (3.5%), Oman (5.1%), Morocco (1.4%), Algeria (4.9%) and the rest of the Arab States. The reason behind these low rates could be shortages in technical schools, though perhaps a more likely reason is that manual work is still socially unacceptable in several segments of society. There is also a negative cultural attitude towards S&T activities that require manual labour. The small output of technicians at the second level perhaps explains one of the reasons behind the low productivity of the manufacturing and agricultural sectors.

General education at the second level in the Arab States

TABLE 1
POPULATION, ILLITERACY, ENROLMENT AND PUBLIC EXPENDITURE ON EDUCATION IN THE ARAB STATES

		Adult illiteracy		Enrolment ratio[1] 1989				
				Second level		Third level		Public education expenditure[2]
Country/territory	Population 1990 (millions)	1990 (%)	% annual reduction 1970-90	%	% tech.	%	% science	(% of GNP)
Algeria	25.0	43	2.82	61	4.9	11	14	10.0
Bahrain	0.5	23	4.26	84	18.0	15	–	5.6
Djibouti	0.4	80	0.97	16	–	–	–	3.0
Egypt	52.4	52	1.12	81	21.8	20	38	6.8
Iraq	18.9	40	2.54	47	13.7	14	33	5.0
Jordan	4.0	20	4.99	70	8.0	35	47	6.2
Kuwait	2.0	27	2.70	90	0.3	18	35	5.1
Lebanon	2.7	20	2.22	67	–	28	45	–
Libya	4.5	36	2.84	–	–	10	–	11.0
Mauritania	2.0	–	–	16	3.1	3	12	6.0
Morocco	25.1	50	2.25	36	1.4	11	59	8.5
Oman	1.5	–	–	48	5.1	4	34	5.5
Palestine	1.6	20	4.99	70	8.0	30	47	–
Qatar	0.4	–	–	85	3.5	24	10	6.0
Saudi Arabia	14.1	38	4.46	46	1.9	12	34	8.6
Somalia	7.5	76	1.23	10	–	3	18	1.5
Sudan	25.1	73	0.64	20	–	3	27	5.5
Syria	12.5	35	2.73	54	6.9	20	31	4.5
Tunisia	8.2	35	3.54	44	13.3	8	31	7.0
UAE	1.6	–	–	64	0.8	9	46	2.5
Yemen	11.7	61	2.08	21	–	2	12	6.1
Total	221.8	42	2.29	52	12.0	13	35	7.0

1. Enrolment ratio is derived by expressing the total enrolment as a percentage of the population of the age group which, according to national regulations, should be enrolled at this level.

2. Estimated.

Source: UNDP (1990, 1991 and 1992), UNESCO (1992), World Bank (1992). Some data are also estimated.

is divided into two streams, with around 50% of students enrolled in each. The first is the literary stream which emphasizes the humanities and social sciences and offers only a small amount of science; the second is the scientific stream which emphasizes mathematics and the natural sciences. Thus this two-stream system deprives around half of the students at this level of adequate exposure to the natural sciences.

SCIENCE IN HIGHER EDUCATION

Enrolment ratio

The average enrolment ratio according to age group at the third level of education, which includes university as well as lower levels beyond the second level, increased in the Arab States from 4.1% in 1970 to 9.5% in 1980, to 10.8% in 1985, and then to 13% in 1989, which represents an average annual rate of 8.77% during 1970-80, 3.55% during 1980-85 and 4.74% during 1985-89. The ratio of 13% is still very low compared with the 37% in industrialized countries. Enrolment ratios are the highest in Jordan (35%), Lebanon (28%), Qatar (24%), Egypt (20%), Syria (20%) and Kuwait (18%). Countries with very low ratios, i.e. less than 10%, are Djibouti, Mauritania, Oman, Somalia, Sudan and Yemen.

Prior to 1950, university education in the Arab world was very limited and highly selective, since only nine universities existed before this date. As the Arab States gained independence, so additional universities were established. Twenty-four were created during the period 1950-69, 31 during 1970-79, and 29 during 1980-90, thus bringing the regional total to 93 in 1990. With the exception of a few Arab States with very low enrolment ratios at the third level, all the others have established ministries or councils for higher education for the purpose of policy formulation and higher education planning.

Undergraduate students in general fields of science

Available data indicate that the number of undergraduate students from the Arab States studying within and outside the Region increased from 0.99 million in 1980 to 1.47 million in 1985, an average annual rate of increase of 8.2% (Qasem, 1989). Assuming this rate were to be maintained during the period 1985-90, the number is estimated to have reached 2.18 million in 1990. The annual rate of increase in the 1980s varied from country to country. Several of the GCC States, namely Saudi Arabia, Qatar, the UAE and Oman, took the lead with ratios higher than 13%. This ratio was also high in Algeria (12.3%) and Morocco (11.8%). Other countries had ratios close to or less than the overall average. Most undergraduate students are concentrated in only a few Arab States; thus 44.2% of the total are in Egypt, 11.8% in Morocco, 8.6% in Algeria and 7.3% in Syria, bringing the total to 71.9% in these four States. The share of the other 17 countries is rather small: for example, the share of the six GCC States is only 7.3%.

It should be noted at this point that the total Arab population in the age group 20-24 was 14.9 million in 1980, 17 million in 1985 and 19.6 million in 1990. Using these figures along with the number of undergraduate students, the enrolment ratios within this age group may be calculated as 6.7% in 1980, 8.6% in 1985 and 11.1% in 1990. These figures are very small indeed.

Table 2 shows the distribution of undergraduate students according to the general fields of science. The share of social sciences and humanities is dominant, increasing to 67.8% in 1990, leaving only 32.2% to be spread across all other fields. While the share of natural sciences increased slightly from 9.2% in 1985 to 10.1% in 1990, the share of medical sciences decreased from 9.2% to 8.1%, engineering sciences also from 9.2% to 8.1%, and agricultural sciences from 5.5% to 4.1%.

These trends are not healthy because the present stage of development in the Arab States requires more doctors, pharmacists, nurses, engineers, agricultural scientists and other specialists to cope with the critical needs of development. The needs of the agricultural sector, for example, exceed by far the output of human resources by universities in agricultural sciences. This is evident from the fact that only 4.1% of all students are in agricultural

TABLE 2
NUMBER OF ARAB UNDERGRADUATE STUDENTS (INSIDE AND OUTSIDE THE REGION) AND THEIR DISTRIBUTION ACROSS THE GENERAL FIELDS OF SCIENCE

Field	Average annual increase 1980-85 (%)	Undergraduate students ('000s) 1985	1990[1]	% of total 1985	1990[1]
Natural sciences	10.4	135.6	222.0	9.2	10.1
Medical sciences	5.6	134.8	176.9	9.2	8.1
Engineering sciences	4.4	172.9	214.8	11.8	9.9
Agricultural sciences	1.7	81.2	88.4	5.5	4.1
Social sciences and humanities	9.4	945.6	1478.5	64.3	67.8
Total	8.2	1 470.1	2 180.6	100.0	100.0

1. Estimated, based on average annual increase during 1980-85.

Source: Qasem, 1989.

sciences. If one quarter of the 88 400 students in this field in 1990 had graduated in 1991, then the output would be 22 100 students, but this output seems somewhat small since the food import dependency ratio for the Arab States is rather high (38%) and continues to increase over time. In terms of health, the average under-five mortality rate in the Arab States is around 100 per 1 000 live births, which is 5.6 times higher than that in the industrialized countries. Furthermore, around 56 million of the Arab population do not yet have access to health services. The very low productivity of manufacturing industry in the Arab States, as mentioned earlier, clearly underlines the need for more engineers in all fields. Even in Jordan, which is known for its relatively good supply of human resources, only 5% of the total labour force in industry are specialized in engineering sciences.

The disparities in the distribution of students according to the field of science may be due to shortages of facilities in the natural, medical, engineering and agricultural sciences, though the primary reason must surely be due to the division of general second-level education into the literary and scientific streams. While those who finish the literary stream can only enrol in the social sciences and humanities at university, only those with the highest grades in the scientific stream are allowed to enrol in the colleges of natural sciences, engineering, medicine and agriculture. This automatically prevents around two-thirds of high-school graduates in general education from going into these fields.

Graduate students in general fields of science

The total number of graduate students studying for Masters or PhD degrees inside and outside the Arab Region increased from 51 400 in 1980 to 78 700 in 1985, an average annual rate of increase of 8.9% (Qasem, 1987). Assuming that this rate prevailed during 1985-90, the number will have reached 120 400 in 1990. High rates of increase in the 1980s took place in the GCC countries (13% and higher), Algeria (12.2%), Jordan (12.4%), Morocco (11%) and Syria (12%). Egypt has the largest number of graduate students; in 1990 these constituted 45.9% of the Region's total. Next come Algeria, with 15.8% of the total, Morocco (12.8%), Saudi Arabia (8.2%), Iraq (4.8%) and Jordan (3.6%). These six countries together have 91.1% of all graduate students in the Arab States.

Table 3 shows the distribution of graduate students according to general fields of science. The situation here is quite at odds with that shown for undergraduates in terms of the high ratio of students in the field of social sciences and humanities. The percentage of graduate students in the social sciences and the humanities was reduced from 40.8% in 1985 to 38% in 1990. In addition, the distribution of graduate students in other fields was quite acceptable, since in 1990 around 13.1% were in the natural sciences, 27.1% in the medical sciences and 11.9% in the engineering sciences. However, the ratio of 9.9% in the agricultural sciences must be considered rather low.

This somewhat balanced distribution, which is in favour of development needs, is a necessary but not a sufficient condition because the total number of Masters and PhD students is indeed small. This can be illustrated by showing the percentage of graduate students to undergraduates. This was 5.2% in 1980, 5.4% in 1985 and 5.5% in 1990: in other words almost static during the 1980s. Unless this ratio is increased to 10% or so, the demand for Masters and PhD degree holders cannot be met. As a consequence of the low number of graduate students, the student to teaching-staff ratio at universities will continue to increase and R&D institutions are destined to remain understaffed.

Around 28% of all graduate students in 1990 were studying for a PhD degree, bringing the total to around 22 000. This is a relatively small number when we consider the need of universities to increase the percentage of PhD degree holders among their teaching staff from the current figure of 57%. As seen from Table 3, the ratio of PhD students is quite high in agricultural sciences (43%). For other fields, the ratios are relatively small in relation to current needs.

The capacity of most Arab universities to absorb graduate students at the Masters degree level is growing, since only 15% of these students are having to pursue their education elsewhere. However, PhD programmes are still limited in number. While around 25% of all PhD students in Egypt study elsewhere, this figure is above 80% for other Arab States. However, it has to be said that a high capacity,

TABLE 3
NUMBER OF ARAB GRADUATE STUDENTS (INSIDE AND OUTSIDE THE REGION) AND THEIR DISTRIBUTION ACROSS THE VARIOUS GENERAL FIELDS OF SCIENCES

Field	Average annual increase 1980-85 (%)	Graduate students ('000s) 1985	1990[1]	% PhD	% of total 1985	1990[1]
Natural sciences	7.35	11.0	15.7	27	14.0	13.1
Engineering sciences	8.41	9.5	14.3	31	12.1	11.9
Agricultural sciences	8.18	8.0	11.9	43	10.2	9.9
Social sciences and humanities	7.39	32.1	45.8	23	40.8	38.0
Total	8.88	78.6	120.4	28	100.0	100.0

1. Estimated, based on average annual increase during 1980-1985.

Source: Qasem, 1987.

provided by the relatively new local universities, for absorbing large numbers of PhD students should not automatically be viewed with favour, since obtaining a good education at this level in industrialized countries is better for development needs in the long term. It is therefore preferable for most Arab universities at this stage to concentrate upon expanding and improving their Masters degree programmes.

Public investment in higher education

Total public investment in all levels of education in the Arab States, expressed as a percentage of GNP, increased from 4.4% in 1980 to 6.2% in 1985, and to an estimated 7% in 1990. This brings the total investment to around US$24 billion in 1985 and around US$30 billion in 1990, which puts the average GNP per capita spending on education at around US$126 in 1985 and US$135 in 1990. Investment in education as a percentage of GNP varied among the Arab States, from above 8% in Algeria, Libya, Morocco and Saudi Arabia to less than 3% in Djibouti, Somalia and the UAE (see Table 1).

Public investment in higher education as a percentage of investment in all levels of education is known only for a few Arab States. Available data indicate that this ratio is slightly higher than 20% in Egypt, Iraq, Jordan and Syria and less than that in other States (UNDP, 1990, 1991 and 1992). If we estimate the average to be 25%, then investment on all levels of higher education was around US$7.5 billion in 1990, or 1.74% of the GNP. This ratio is equivalent to 14% of the expenditure on the military during the same year. It can safely be said that the upper limit for the average expenditure on universities was 20% of the total for all levels of education, or US$6 billion in 1990.

RESEARCH AND DEVELOPMENT

Recent data on R&D inputs for all or most Arab States are not available. However, we will use the data for 1985 prepared by Professor S. Qasem in 1987, and extrapolate in order to arrive at data for 1990, after making reasonable assumptions (Qasem, 1987). Most Arab States have already established organizations such as ministries of higher education and scientific research or councils for science and technology for S&T policy formulation and planning. We will attempt in this section to present information on the status of research at universities and R&D centres.

R&D at universities

Research and development activities at universities are essentially carried out on an individual basis by faculty members aided by research assistants, and at specialized R&D centres of the universities which are managed by a small staff using the services of faculty members for research purposes. The establishment of such centres was largely in response to economic needs where R&D had to be performed on a multidisciplinary basis. There are around 45 such centres attached to universities, working on research related to agriculture, medicine, water and marine sciences, environment, computers, remote sensing, economics and other applied sciences.

The number of scientists (faculty members) in all general fields of science in Arab universities went from 35 800 in

1980 to 51 300 in 1985, increasing on average at an annual rate of 7.5%. When this rate is applied to the period 1985-90, we see that the total was set to reach 73 500 in 1990. In that same year, the number of PhD degree holders was to reach 40 600, or 55.2% of all graduate degree holders, while the number of those holding a Masters degree was to be 32 900 (44.8%). Egypt has around 45% of all scientists at the universities in the Arab States. Algeria has 13%, and Morocco 9%, while Saudi Arabia and Iraq each have 8%. These five countries together have 83% of all scientists working at universities in the Region.

Table 4 shows the number and distribution of scientists according to general fields of science. The full-time equivalent (FTE) number of R&D scientists is obtained from the total by assuming that the teaching staff spends on average between 20% and 25% of its total time on R&D activities. An equivalent FTE number of research assistants is added to obtain the total figure. Thus, the total FTE number of researchers and assistants reached 29 400 as a lower limit and 36 800 as an upper limit in 1990, giving the ratios of 132 and 166 respectively of FTE scientists per million population. The distribution of research scientists among the various fields of science, as seen in Table 4, is acceptable, with the exception of the agricultural sciences which do not receive their proper share in terms of research personnel.

Research investment at universities includes salaries, benefits, facilities and services, in addition to grants or contract research funds from various sources. Generous research grants are provided by universities in Kuwait, Saudi Arabia and the rest of the GCC countries; on the other hand, such grants are limited in the other Arab States. It is assumed that 20% of investment on all levels of education is devoted to university education, bringing the total investment in universities to US$6 billion in 1990. Since, on average university scientists devote 20% of their time to R&D as a lower limit and 25% as an upper limit, then R&D expenditure at universities would amount to US$1.2 or US$1.5 billion respectively and, allowing 10% for external funding, the total R&D expenditure at universities would amount to between around US$1.32 billion and US$1.65 billion. These figures are equivalent to between 0.31% and 0.38% of the 1990 GNP. The 20%

TABLE 4
NUMBER OF SCIENTISTS WITH MASTERS AND PHD DEGREES (FACULTY MEMBERS), FTE RESEARCHERS AND ASSISTANTS AT UNIVERSITIES IN THE ARAB STATES, ACCORDING TO GENERAL FIELDS OF SCIENCE

Field	Average annual increase (%) 1980-85	Scientists with Masters or PhD degree ('000s) 1985	1990[1]	FTE R&D ('000s) 1990[1] Scientists[2]	Assistants	Total	% of total	Share of R&D expenditure (%)
Natural sciences	8.2	9.9	14.6	3.6	3.6	7.2	19.6	23
Medical sciences	7.6	10.7	15.4	3.9	3.9	7.8	21.2	25
Engineering sciences	8.0	7.0	10.3	2.6	2.6	5.2	14.1	16
Agricultural sciences	5.9	6.0	8.0	2.0	2.0	4.0	10.9	13
Social sciences and humanities	7.3	17.7	25.2	6.3	6.3	12.6	34.2	23
Total	7.5	51.3	73.5	18.4	18.4	36.8	100.0	100

1. Estimated, based on average annual increase during 1980-85.
2. The numbers are obtained by assuming 25% of time devoted to R&D.

Source: Qasem, 1987.

value used for time devoted to R&D by university teaching staff is reasonable since a comprehensive survey conducted on S&T potential in Jordan came up with a rate of 18% (Daghestani and Shahateet, 1988).

R&D expenditure at universities is not distributed according to the scientific manpower figures for each general field of science shown in Table 4, because on average the estimated cost of research in the social sciences and the humanities in the Arab States is around 60% of that in other scientific fields. The distribution of R&D expenditure according to fields is therefore estimated to be 23% for natural sciences, 25% for medical sciences, 16% for engineering sciences, 13% for agricultural sciences and 23% for social sciences and humanities.

R&D institutions

The Arab States started to establish R&D centres to complement the research effort at universities in performing applied scientific research, increasing work in experimental development, adopting a multidisciplinary approach to problem solving, and establishing closer links with the productive sectors. Research organizations come under various names, such as departments, directorates, institutes and centres; however, for the purpose of this article we shall use the word centre to cover all such institutions.

It is estimated that the number of R&D centres in the Region reached 265 in 1990. Around 65 centres were established during 1950-69, 170 during 1970-79, and 30 during 1980-90 (Qasem, 1987). The number of R&D workers (scientists plus assistants) in each centre varied greatly – from as many as over 3 000 to as few as 50. The total number of R&D scientists holding Masters or PhD degrees during 1985 was around 8 800. Although the actual number of employees at these centres is more than four times this figure, the number of research assistants is around twice the number of scientists, bringing the total of R&D workers in 1985 to 26 400, or 138 per million population. Using the same formula and assuming the number to increase at an annual rate of 5%, the FTE number of R&D workers was estimated to reach 33 700, or 152 per million population, in 1990.

Table 5 shows the distribution of this estimated number of R&D workers in 1990 according to nine fields of science. It is to be noted that the share of agriculture and food was 44%, while the field of petroleum, petrochemicals and chemicals came next with 13.9% of the total, followed by energy (8.9%), mining (8.6%), and natural sciences (6.2%). As can be seen, the nine fields shown in this table can, in fact, be reduced to our former five, since agriculture, water and irrigation, and arid lands can be considered part of agricultural sciences, and energy, the petrochemical industry and mining fall into the category of engineering sciences.

The reason for including nine fields in Table 5 was to

TABLE 5
ESTIMATED NUMBER OF R&D WORKERS (ON FTE BASIS) IN R&D CENTRES IN THE ARAB STATES, BY FIELDS OF SCIENCE, 1990

Field	Number of centres	FTE R&D workers ('000s)	% of total
Agricultural sciences	87	16.7	49.7
Agriculture and food	61	14.8	44.0
Water and irrigation	16	1.0	3.0
Arid lands and remote sensing	10	0.9	2.7
Natural sciences	41	2.1	6.2
Medical sciences	32	1.6	4.7
Engineering sciences	92	10.6	31.4
Energy (nuclear electric, solar, etc.)	29	3.0	8.9
Petroleum, petrochemicals and chemicals	22	4.7	13.9
Mining, materials, electronics, etc.	41	2.9	8.6
Social sciences (economics)	13	2.7	8.0
Total	265	33.7	100.0

Source: Qasem, 1987.

show how small the numbers of FTE researchers are in the fields of water and irrigation, arid lands, and the petroleum, petrochemical and chemical industries. As stated in a previous section, water and arid lands are critical issues in most Arab States, but the number of researchers devoted to them is small compared to the scale of the problems. Furthermore, the number of FTE researchers (4 700) devoted to the petroleum, petrochemical and chemical industries falls short of the need to develop the know-how to use the enormous oil and gas resources of the Arab World in manufacturing industries. In addition, the number of FTE researchers in the engineering sciences is 10 600, which is small when we consider that the Arab States invested over US$120 billion in industry during the course of the last 15 years.

Most of the human resources at R&D centres are concentrated in Egypt, its share being 56% of the total in 1990, with Iraq at around 11% and Saudi Arabia 12%, and the remainder being distributed among the other 18 Arab States.

There are no reliable data on expenditure in R&D centres in the Arab States, but a reasonable estimate can be made by taking the figure for R&D expenditure at Arab universities and adjusting according to the relative numbers of FTE researchers in R&D centres and universities. Doing this, we obtain US$1.51 billion, an amount which represents 0.35% of the total GNP of the Region.

Summary of R&D workers and expenditure

The data presented so far indicate that the estimated total number of R&D workers in universities and R&D centres increased from 52 100 in 1985 to 70 500 in 1990, representing an average annual increase of 6.2%. The latter total constituted 318 scientists (FTE) in R&D per million population, still far below the average of around 3 600 in the developed countries (UNESCO, 1991). Table 6 shows the distribution of these scientists among the general fields of science in the Region.

The total investment in R&D at universities and R&D centres increased from around US$2.3 billion in 1985 to US$3.2 billion in 1990, the latter constituting 0.75% of the GNP, a very low value compared to the average of 2.92% of GNP in developed countries (UNESCO, 1991). Table 7 shows the estimated distribution of total R&D investment among the general fields of science.

TABLE 6
ESTIMATED NUMBER OF RESEARCHERS (FTE) AT UNIVERSITIES AND R&D CENTRES IN THE ARAB STATES, 1990

	Full-time-equivalent (FTE) ('000s)				FTE per million population
Field	Universities	R&D centres	Total	% of total	
Natural sciences	7.2	2.1	9.3	13.2	42
Medical sciences	7.8	1.6	9.4	13.3	42
Engineering sciences	5.2	10.6	15.8	22.4	71
Agricultural sciences	4.0	16.7	20.7	29.4	93
Social sciences and humanities	12.6	2.7	15.3	21.7	69
Total	36.8	33.7	70.5	100.0	318

Source calculated from data in Tables 4 and 5

TABLE 7
ESTIMATED TOTAL R&D EXPENDITURE IN UNIVERSITIES AND R&D CENTRES IN THE ARAB STATES, 1990

	R&D expenditure		
Field	US$ billion	% of total	% of GNP
Natural sciences	0.46	14.4	0.11
Medical sciences	0.46	14.4	0.11
Engineering sciences	0.78	24.4	0.18
Agricultural sciences	1.04	32.5	0.24
Social sciences and humanities	0.46	14.4	0.11
Total	3.20	100.0	0.75

Source calculated from data in text and Table 4.

Problems and trends

The objectives of carrying out R&D at universities are not only to generate new knowledge as a noble objective in itself, but also to improve the capabilities of the staff to instruct students, especially graduate students, and to serve the social and economic needs of the country. On the other hand, R&D centres were specifically established to generate new knowledge and use this knowledge to serve the country. In both cases, although applied research (R) has been performed, little development (D) work has taken place. In general, R&D activities in the Arab States have not made a visible impact on the various sectors of the economy because the socio-economic system often bypasses the scientific community as a result of over-reliance on technology trade, turn-key projects and licensing agreements with foreign firms. Consequently, the lack of demand for endogenous R&D has caused the lack of supply in terms of R&D scientists and investment.

In spite of all this, the scientific community should not be released from its responsibilities in carrying out R&D relevant to actual needs and in pursuing the development required for the application of R&D results. After all, the scientific community makes its own rules and regulations that promote the publication of R&D results, but there is not the same incentive for further effort beyond publication. Several R&D institutions in the Arab States did start to promote contract research with the productive sector in the 1980s. For example, the Kuwait Institute for Scientific Research (KISR) generated around 50% of its annual expenditure from contract research. Similarly, the Royal Scientific Society in Jordan, which performs industrial research and provides S&T services, was able to cover 100% of its expenditure in 1992 in a similar way. In order to move in these directions, R&D institutions in the Arab States have to find new ways of operating in order to justify whatever little public investment has been made available to them.

It should be added that very few private-sector organizations have their own R&D centres, and that when they do they normally indulge in S&T services such as studies or quality control. Industrial research units are more prevalent in export-oriented industries that compete in the world market, but these are relatively few. Other industries that are import-substitution oriented are often well protected by high import tariffs which lead to captive local markets; consequently demand for R&D is indeed small.

FAKHRUDDIN AL-DAGHESTANI is the Director of the Centre for International Studies at the Royal Scientific Society in Jordan. Dr Daghestani, who is a former President of the Royal Scientific Society, obtained his PhD in Mechanical Engineering from the University of Missouri in the USA and was awarded the *Das Grosse Verdienstskreutz mit Stern* medal by the President of the Federal Republic of Germany in 1985. He is a Founding Fellow of the Islamic Academy of Sciences and has been one of its Council Members since 1986.

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AFRICA

Thomas R. Odhiambo

In the January 1993 issue of the monthly magazine *The Tatler*, a writer distinguished between heroism and celebrity, and characterized heroes as 'men and women who tower above the ordinary in terms of bravery, charisma and leadership' (Anonymous, 1993). Indeed, heroes are 'people who have displayed courage by adhering to sets of values that lie outside the norm'. They are not demigods or Greek gods and, as the writer reminded us:

'The Greeks, who really invented heroes, never meant them to be real. Heroes were gods or sons of gods; they were never supposed to be ordinary people who had ordinary wives and families and day jobs and bad backs and dandruff. The Greeks had a word for people who wanted to imitate the gods and the heroes – hubris; the arrogant, reckless presumption that you could behave like superman, and that always led to nemesis; the retribution of the gods.'

Africa does not require demigods. But it surely needs modern heroes, who fight against conventional wisdom, deep prejudice and ingrained injustice. Africa needs heroes who can innovate and raise the continent out of its present developmental lethargy and dependence syndrome.

Science, and its twin interactive partner, technology, hold the in-built promise of permitting their practitioners to break away from the normal rut and bring into play a new way of looking at the challenges of life, living and livelihood. It is in this context, therefore, that Africa needs its heroes; in science and education, in entrepreneurship and industry, and in economic management and development, for the long haul to redevelopment. The continent has virtually lost the sense of heroism during and since the 500-year-long Diaspora which ended three decades ago with the reacquisition of political independence. Such heroic endeavour requires the continuing transboundary movement of people and knowledge, of ideas and technologies.

One of the factors responsible for the accomplishments of the Pharaonic civilization in Egypt, which spanned three millennia from about 3700 to 750 Before Our Era, was the extensive communication between Egypt and the Near East, and the rest of Africa, particularly the Nilotic Sudan and the neighbouring population centres in Africa south of the Sahara. Archaeological evidence of the general use of incense and obsidian, both foreign to the Nile Valley, attest to the strong communication and trade links between Egypt and the rest of Africa (Mokhtar, 1981). This sense of transboundary linkages and intellectual intercourse, especially in science and technology (S&T), is a renewed imperative for Africa's future progress during the emerging post-colonial era.

POLICY FRAMEWORK FOR INTER-AFRICAN S&T COOPERATION

During the first half of this century, African countries cooperated most intimately with the S&T institutions of the metropolitan powers. There was an insignificant degree of inter-African cooperation, except within a single-power colonial zone, such as the Belgian areas of geopolitical influence (which were to become Rwanda, Burundi and Zaire in the post-colonial era) or the French (such as the Central African zone, encompassing what later became known as the Congo Republic, Gabon, the Central African Republic, Cameroon and Chad). The first important attempt at inter-African S&T cooperation began early in the 1950s in the run-up to political independence in most of the African continent.

In his seminal book, *Science in the Development of Africa*, published in 1958, Dr E.B. Worthington, a British freshwater biologist and S&T policy analyst who worked for most of his life in Africa, argued the case for inter-African S&T cooperation in a most telling manner:

'In the competitive world of the 20th century, it is difficult for any small country to be independent of its neighbours and at the same time provide the requirements of modern civilization for its people, unless it is unusually well endowed with natural and human resources. This principle has special force in Africa where local conditions have led to economic specialization, not merely in one major industry such as agriculture or mining, but in particular sections of it, such as cotton, cocoa or copper. Any measures for pooling the resources of neighbouring countries with different specialities lead to all-round advantages in reducing the economic risks. As in economics, so in science, considerable specialization has taken place in different territories, so that collaboration, or even a full exchange of information, could give great benefits.' (Worthington, 1958).

It was this type of consideration at metropolitan governmental level that had eventually led to the establishment of the Commission for Technical Cooperation in Africa South of the Sahara (CCTA) in 1950 by the six colonial governments then operating in Africa – Belgium, the UK, France, Portugal, the Federation of Rhodesia and Nyasaland, and the Union of South Africa. A similar initiative by scientists from these six countries led to the creation of the Scientific Council for Africa South of the Sahara (CSA) in the same year. Thus, the two organizations sprang from two distinct roots: the CCTA for mutual assistance by the metropolitan powers for administrative and political reasons; the CSA for S&T cooperation and consultation arising from the expressed wishes of the citizen scientists of those countries. In practice, the two bodies came to work closely and in concert.

While the CSA (with its headquarters in Bukavu, Zaire) acted as the principal scientific and technical adviser of this mutual assistance system, with its functions very much concerned with science policy development and implementation, the CCTA (with its headquarters in London, UK) became the executive and financial authority, and concentrated upon managerial policy and resource allocation.

In order to ensure that existing S&T institutions in Africa were aggregated under the CSA umbrella, the CCTA promulgated a provision in its Establishment Agreement, signed in London in January 1954, which was to place under the aegis of the CSA the following inter-African organizations: the Inter-African Bureau of Epizootic Diseases, the Tsetse Fly and Trypanosomiasis Permanent Inter-African Bureau, the Inter-African Bureau for Soils and Rural Economy, the Inter-African Labour Institute, the Inter-African Pedological Service. Later, other similar cooperative scientific organizations in Africa south of the Sahara were added to this group.

The geographical purview of the CCTA changed in February 1962 when at the 17th session of the CCTA held in Abidjan, Côte d'Ivoire, the words 'South of the Sahara' were deleted from the title of the Commission, and the Secretary-General was requested to 'awaken the interest of the Governments' of Ethiopia, Sudan, Togo and the North African region in the activities of the Commission. This was a bold step, and one which the industrialized states have reneged upon in the post-colonial era. Similar steps were taken by the CSA at its 13th meeting in September of that same year in Muguga, Kenya. The two organizations therefore extended their umbrella to include the whole continent of Africa, while taking the necessary steps 'to cease all relations with South Africa and Portugal' (Publication no. 92 of the CCTA, Lagos, 1964). In 1961, Nigeria had offered to house the CCTA headquarters in Lagos, Nigeria (away from its original home in London), and in moving this important organ for technical cooperation, the CCTA authorities demonstrated an underlying philosophy:

'CCTA, an instrument of African solidarity, is likewise a bridge between Europe's science and Africa's needs. There are other, wider bridges which may carry more traffic, but the one built and maintained by the Commission will remain open whatever political fluctuations may occur.' (CCTA/CSA/FAMA: Inter-African Cooperation, 1962).

The CCTA became, in part, an effective inter-governmental organ for technical cooperation in Africa because of its great reliance on the S&T policy capacity of its sister body, the CSA. The latter guarded its independence fiercely. Thus, its members were presumed to 'serve in a spirit of complete impartiality and objectivity, regardless of political considerations and without reference to their national governments'. Three freedoms seemed to have been essential for the demonstrated effectiveness of the CSA:

- freedom to choose its members irrespective of their nationality (it needed only to inform the CCTA of these appointments);
- freedom to hold its meetings in any of the Member Countries of the CCTA;
- freedom to work in liaison with other S&T organizations and other countries, even though linked closely to CCTA.

As a result of this the CSA had proved a pillar of exceptional strength to the CCTA at the time of the latter's takeover in 1964 by the recently established continental body, the Organization of African Unity (OAU).

The new order

The Scientific, Technical and Research Commission (STRC) of the OAU was the successor organization to the CCTA.

Indeed, among the issues dealt with in the First Ordinary Session of the OAU Council of Ministers, held in Dakar in August 1963, was the future of the CCTA. This move needs to be seen in the context of the OAU Charter which, in Article II dealing with the purposes of the OAU, states in para. 2 that 'to all these ends, the Member States shall coordinate and harmonize their general policies' in six fields, two of which deal with 'health, sanitation, and nutritional cooperation' and 'scientific and technical cooperation' so as 'to coordinate and intensify their cooperation and efforts to achieve a better life for the peoples of Africa'.

The Scientific Council of Africa (SCA) likewise became the successor organization to the CSA. The other agencies which operated under the CCTA were largely transformed into what became known as the STRC Sub-Regional Offices. These consisted of the Inter-African Bureau for Animal Resources (IBAR), based in Nairobi, Kenya; the Inter-African Phytosanitary Council (IAPSC), based in Yaoundé, Cameroon; and the Inter-African Bureau for Soils (BIS) which was based in Bangui, Central African Republic, but has now ceased to function. The STRC has, however, acquired other new activities over time – such as the coordination offices for the Semi-Arid Food Grain Research and Development Project (SAFRAD), based mainly at Ouagadougou, Burkina Faso; the African Centre for Fertilizer Development, based in Harare, Zimbabwe; and the Agricultural Management Training Programme for Africa (AMTA).

There is no doubt that African economies must move deliberately toward integration – not as a distant dream, but as a pragmatic matter of urgent necessity (Odhiambo, 1991). Such a cooperative framework was eloquently enunciated in the 1991 policy statement made by the United Nations Economic Commission for Africa:

'The political balkanization of the continent into arbitrary nation-states elicits from Africa the understandable impulse to restructure the fragmented region into a more coherent and stronger economic and political entity. The African sense of oneness and solidarity also sparks off natural sentiments for increased socio-economic cooperation. At the economic level, the numerous obstacles to genuine development that individual African countries confront as a result of their limited and fragmented economic space have provided an objective rationale and galvanized the African resolve to pursue and achieve the goal of collective self-reliance. Overall, Africa sees self-reliance as both the goal and the means through which the region will eventually find its true identity, full dignity and historic strength. It is also the goal and the means by which the region will find the capacity to master its resources, its development, and its future.' (UNECA, 1989).

In the selfsame spirit, the OAU has eloquently articulated its continental goals to achieve integrated socio-economic development in an environment of self-reliance and sustainability, as evidenced in the *Lagos Plan of Action for the Economic Development of Africa, 1980-2000*, an expression of faith by the African Heads of State and Government meeting in Lagos, Nigeria, in April 1980:

The Lagos Plan of Action has clearly expressed its philosophy that 'since Africa's greatest asset is its human resources, full mobilization and effective utilization of the labour force for national development and social progress should be a major instrument of development.' (para. 91).

'In order to achieve the industrial development objectives ... Member States decided to take all measures at the national, sub-regional and regional levels in the areas of human resources, natural resources, financing and promoting institutions in order to lay the foundation for the total and complete mobilization of all energies in ensuring the success of the gigantic task undertaken.' (para. 53).

The Member States should harmonize national natural resource development policies 'with a view to creating a favourable environment for cooperative efforts ... in the development of their natural resources to meet socio-economic needs of their peoples.' (para. 78, e).

A profound science policy change is needed to bring science to the development of the continent: 'this would require, among other things, the generation of financial resources and political will and courage on the part of policy and decision makers of the continent to induce a profound change with far-reaching effects on the use of science and technology as the basis of socio-economic development as a matter of utmost importance and urgency at this fateful juncture of history.' (para. 119) (OAU, 1981).

The operational agenda of the OAU has been – during the first three decades of its existence – an overwhelmingly political one: on decolonization, abolition of apartheid, resettlement of refugees, resolution of interstate conflicts, etc. This circumstance is understandable, as it is of historical import. Of the 925 resolutions passed by the OAU Council of Ministers over the 20-year period 1963-82, a mere 3% dealt with solidly scientific and technological issues (and probably 12.5% with associated scientific and technological matters). With the lack of science-based development in Africa so glaring in the present technology-dominated world, it is important that equal attention to research and development (R&D) as an engine of socio-economic development be paid by the OAU, its organs, and other regional and national development entities.

This radical change requires the transformation of the present weak STRC into a robust and efficient mechanism; the development of strong links between the management of the OAU General Secretariat and the STRC directorate; and the identification of STRC's agenda with the needs of its continental constituency in Africa and its national counterparts at the national and sub-regional levels.

PERFORMANCE OF THE OAU'S SCIENCE AND TECHNOLOGY STRUCTURE

The picture of the STRC that emerges as we approach the end of the present century is not one of an effective S&T arm of the OAU. The STRC is not known outside a small circle of dedicated specialists and governmental planners in Africa. The SCA is even less in the sunshine: indeed, it is almost unknown. A comparison between the STRC and SCA today, and the CCTA and CSA of yesteryear, is not flattering.

The CCTA met regularly, once a year at least, and issued comprehensive annual reports which were a source of scientific advice and technological pointers for the future. The Commission was a centre of activity in policy formulation and resources mobilization, and the Member Governments heeded its recommendations. The STRC, on the other hand, lacks presence and credibility in its present operational state, and its advice only rarely draws attention, the few examples being in the field of traditional medicine and the rinderpest campaign.

The SCA is moribund, and has met only twice since the beginning of 1990. It cannot be said to have a central core of programme concerns or science and technology policy; nor can it be considered an advisory and consultative body that can give coherent advice to any important organ of Africa – let alone the STRC.

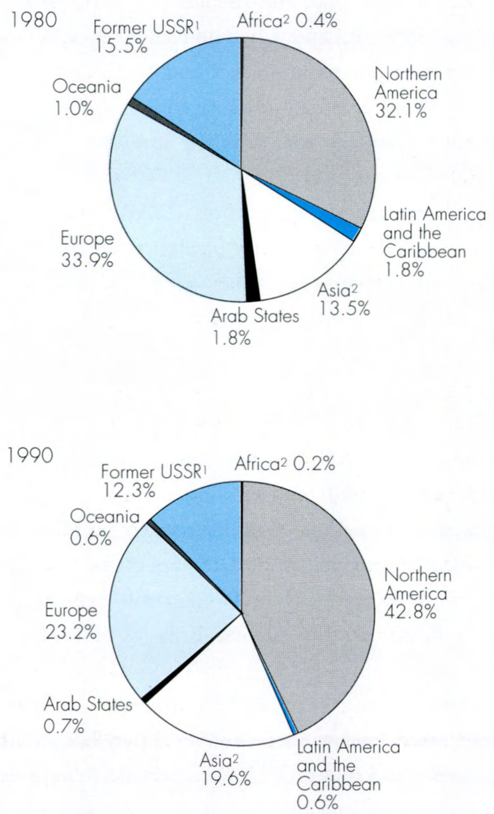
The existing sub-regional offices (IBAR, IAPSC) have not had a major external review of their strategic plans or their scientific performance. They have therefore missed opportunities for finding a new perspective to match the changing needs of the continent, and have not looked afresh from time to time at their achievements in relation to their respective mandates. IBAR did institute a few years ago a system of convening meetings of directors of veterinary services and ministers responsible for livestock development; two such meetings have so far been convened and these have provided important inputs for developing programme priorities. Such a forum could well prove a means of R&D priority setting if it were to become institutionalized.

New programmes (e.g. AMTA, the Project for the Integrated Development of the Fouta-Djallon Highlands of Guinea, and the Project on Coastal Erosion) have been approved for implementation without a comprehensive

TABLE 1
STRC AND ITS AFFILIATES: APPROPRIATIONS AND EXPENDITURE, 1983/84-1987/88

	Appropriations (US$ millions)	Actual expenditure (US$ millions)	Funds utilized (%)
Administrative and other expenses	5.18	3.88	74.9
Operational costs	2.48	1.11	44.8
Total operations	7.66	4.99	65.1

FIGURE 1
R&D EXPENDITURE BY GROUPS OF COUNTRIES: ESTIMATED PERCENTAGES FOR 1980 AND 1990



1. Data refer to 'expenditure on science'.
2. Excluding Arab States.
Source: UNESCO *Statistical Yearbook*, 1992.

contextual examination of the comparative advantage that the STRC has in their implementation – even though the programmes can be of value in themselves.

The morale of the scientific and professional staff is abysmally low, because of the selection procedures which circumvent the peer review process, the lack of incentives to maintain excellence, and the absence of a system of periodic performance evaluation which concentrates on scientific achievement and successful project implementation. Further, the financial support to the STRC and its associated institutions has been both uncertain and understated. For example, in the five-year period 1983/84-1987/88, only 65.1% of the budget for STRC and its affiliates was available for operations (Table 1).

The OAU is not alone in being parsimonious in its support of R&D in Africa. The R&D expenditure as a proportion of the gross national product (GNP) for Africa as a whole was a mere 0.28% in 1980, while Asia spent 1.40% of its GNP on R&D, and North America a massive 2.23%. This appropriation had worsened in Africa by 1990 (it dropped to 0.25%), while in Asia and North America the proportion had increased (to 2.05% and 3.16%, respectively) (UNESCO, 1992). The financial level of this support becomes demonstratively insignificant when one considers that, by 1990, Africa's share of world R&D expenditure constituted only 0.2% of the whole (see Figure 1).

It is our belief, nonetheless, that the OAU has provided a unique opportunity for Africa's geopolitical leadership to work closely and in a complementary manner with the scientific leadership as exemplified by the STRC-SCA axis. We need now to enlarge this opportunity by beginning to consider Africa as humanity's last frontier on Earth.

AFRICA, EARTH'S LAST FRONTIER

In the prophetic words of Gerard Piel, the editor of the monthly magazine, *Scientific American*: 'The African frontier is overdue for action – by indigenous initiative and external assistance – on development.' (Piel, 1992).

If Africa is to build on this vision and its magnetic pull, then it must begin to will its own future, and to create the necessary environment which will enable that willed future to be realized and nurtured.

African leadership in the key endeavours of its society – in scientific research and technology development, in the industrial sector and business enterprise, in the geopolitical and geo-economic arena, and in the ethical and cultural spheres – is fractured and anchorless. Africa carries the prospect of a fractured self-image, a fractured society and a fractured future.

The present is a rare moment in the history of the peoples of Africa. Other regions, other peoples have faced such cataclysmic epochal moments before: the biblical exodus of Jews from Egypt; the utter devastation and defeat of Japan in the Second World War; and North America immediately after the Great Depression. The African continent has reached its nadir; it now needs to dream a new vision, and to design a new willed future. That future cannot continue to carry the burden of material poverty and scientific illiteracy that overwhelms Africa's current development programmes. In Africa some 1.116 billion people live well below the poverty line of US$370 per year, some 60% being women and 47% of the overall African population being poor (Repnik, 1991). Poverty in science is even more crucial than the immediate poverty of the material kind – because science can well determine the future.

It is clear that nations at the forefront of modern development, as we approach the end of the 20th century, are those that have invested enormous resources over a considerable time in three major areas: first, in the establishment and nurturing of a stable, well-supported S&T system; second, in the promotion of mission-oriented research in the basic sciences, coupled with a long-term strategy for technology development; and third, in the institutions of well-articulated programmes for 'the education of a large, technologically literate work force' (Brown and Sarewitz, 1991). An example of this coherent translation of a vision for science-led development is dramatically given by the Republic of Korea. Within a single generation, from 1962 to 1988, the country's GNP increased from US$2.3 billion to US$169 billion, and this was accompanied by a national investment in R&D which grew from 0.24% of the GNP in 1962 to a massive 2.1% in 1988. Taiwan and Thailand are each following this same pattern (Brown and Sarewitz, 1991).

The leap from a pedestrian, agrarian, subsistence economy to a vibrant, mixed agribusiness and industrial manufacturing economy, in the space of three decades, was only made possible by the installation of a single-minded national education and training ethos at all levels of the education system – for R&D, for engineering implementation and technological support, and for the management of the business and economic enterprise. The national commitment kept the long-term goal clearly in sight, and was not diverted by prospects of external assistance taking over the national momentum targeted on this objective.

This revelation should constitute a beacon to Africa – whose development ship is still drifting in the economic backwaters a generation after independence from colonial rule. The motor that will impel the ship away from the debilitating, degrading and diseased backwaters to a new sunlit, confident, hopeful destination is the Africans' own deliberate commitment to their own willed future. Africa's friends can only provide assistance to a limited degree towards the continent's development.

In addition, Africa must begin to look gift horses in the mouth – particularly when it comes to assistance for the establishment and nurturing of Africa's own S&T capacity, which is a vital element for modernizing and invigorating the pace of the continent's self-sustaining social and economic development.

Let us first consider the contribution of one of the major donors to development efforts in the developing regions of the world, the USA. Although the USA has formally concluded numerous S&T agreements with developing countries, there is relatively little funding provided by its government for implementing them (Brown and Sarewitz, 1991). By 1989, there were in force 165 bilateral cooperative agreements in the field of S&T between the USA and 38 developing countries. In that year, the total funding allocated to the implementation of these agreements amounted to just over US$31 million. Of this amount, US$26 million went to support cooperative agreements in only four countries (China, Egypt, India and Pakistan) – leaving US$5 million to fund S&T agreements with the remaining other 34 developing countries, and suggesting that countries with already significant S&T infrastructures are those that benefit more from this US funding.

Congressman George Brown Jr. recently concluded that the example of the Republic of Korea, and the other Asian newly industrialized countries (NICs), has not yet convinced the USA to enter into cooperative agreements that would truly launch developing countries into robust, science-led, self-sustaining economies.

'In spite of such examples (of South Korea, Taiwan, and Thailand), efforts by the United States to promote economic development abroad have never included a comprehensive approach to science and technology.

Although "technical assistance" has been an integral part of United States development aid since the late 1940s, it has not served to foster an independent S&T capability in developing nations. Moreover, the S&T budget for the Agency for International Development (AID) is almost entirely devoted to research carried out by the United States scientists on specific, and often urgent, developmental problems, not to institution building. Of the US$300 million operating budget for AID's S&T bureau in 1991, a mere US$15 000 was slated for joint research with scientists from less developed countries.' (Brown and Sarewitz, 1991).

Consequently, the philosophy of some countries towards developing nations does continue to focus on supplying technology and experts – rather than contributing to the establishment and development of a self-sustaining and durable indigenous S&T capacity.

Other countries favour technical assistance for S&T capacity building and binational cooperation, such as is illustrated by the Swedish Agency for Research Cooperation with Developing Countries (SAREC).

SAREC's bilateral cooperation with selected countries in Africa and other developing regions of the world is of two types: *capacity-emphasizing cooperation* that concentrates on building and strengthening research capacity, particularly in those countries with weak S&T infrastructures (which includes most African countries with cooperative agreements with SAREC); and *result-emphasizing cooperation* that concentrates on the solution of some selected research problems clearly relevant to the development agenda of the region, in cooperation with countries with a sizeable capacity in S&T (such as Argentina in Latin America and India in South Asia) (Bhagavan, 1992). The philosophy behind these S&T development cooperation strategies is to construct a sound, viable base for science-led development in those countries, as Bhagavan recently paraphrased under SAREC's policy formulation:

'To become eventually self-sustaining, the capacity-building process must be firmly rooted in the developing country institutions themselves, with adequate resources put at their disposal, and with the reassurance that their links to scientifically advanced institutions abroad will be longstanding and durable to ensure the consolidation and the continuity of the learning process.' (Bhagavan, 1992).

Neither the recruitment of expatriate scientists and technologists for staffing developing-country S&T institutions – a process that has intensified in most African countries over the last three post-independence decades – nor the despatch of students for study abroad for long periods of their most formative years from a scientific standpoint, can by themselves achieve the goals of 'sustainability in capacity building' (Bhagavan, 1992). The process of capacity building must be securely and consistently anchored within the developing countries themselves, linked to effective capacity utilization.

This is not to say that Africa must close its borders to international influences and to international cooperation. Far from it. While centring and energizing S&T capacity building and utilization within Africa, the continent must thoroughly imbue its emergent development-conscious S&T community in at least three new and innovative ways:

First, the internationalization of the S&T experience of African doctoral graduates who have completed their entire undergraduate and postgraduate education in Africa by placing them for one to two years in first-rate, advanced laboratories in foreign countries, whether developing or industrialized, that are undertaking relevant R&D. This tactic is targeted to further stretch their intellectual conceptual framework, while strengthening their professional assurance. Because such travelling scientists have a strong home base already, they are likely to know what specifically they want to derive from their foreign scholarly sojourn and to fashion more durable scientific linkages.

Second, the intensification of postgraduate research internships within Africa's centres of excellence, for African S&T students who have undertaken undergraduate studies as well as preparatory postgraduate courses in industrialized countries. Such internships are most productive for those internees undertaking doctoral degrees. A scheme of this genre is the African Dissertation Internship Award Programme (ADIAP) that is sponsored by the African Academy of Sciences, and funded by the Rockefeller Foundation. The programme enables African postgraduate students undertaking doctoral studies in the USA in the fields of social sciences, health and agriculture to do their field research in Africa under the interactive supervision of their American as well as African supervisors. The Academy plays a monitoring and follow-up role, and convenes periodic research conferences of the awardees, during which highly experienced resource persons in Africa give seminars in their own specialist fields. Since it was established in 1987, 168 internees have already benefited from ADIAP. We need to extend this concept to doctoral students studying in the whole of the Americas, in Europe, and in Asia and the Far East.

Third, the inauguration of a junior professional associateship programme for young S&T practitioners, using the emerging centres of excellence in Africa as their loci. There is no doubt that, at today's scientific tempo, newly graduated young professionals are wont to be unsure of themselves. They may indeed have already acquired the necessary intellectual, scientific and technological methodologies in the course of their scientific education or professional training. This may be regarded as their tool-acquisition phase. What they desperately require is to enter the tool-utilization phase, under a master tool-user and tool-maker, working within an enabling environment where the making or using of tools becomes an exhilarating and enriching experience. If we can carefully place our bright and acquisitive young doctoral graduates and professionals, both male and female, in such environments within Africa on a sandwich basis for three to six months each year over a period of three to five years, then we are likely to nurture along a new crop of productive, self-confident, thrusting professionals, scientists and scholars that are surely anchored in the African S&T landscape, creating new growth points in R&D, the educational endeavour and the industrial-business enterprise.

A precondition to allow this new paradigm of science-led development to germinate successfully in Africa is that the peoples of Africa must re-integrate science into their culture. The African Diaspora did more than simply disrupt the social and economic fabric of African society. It froze the natural evolution of the peoples' culture into an elemental entity for the mere survival of the society. For more than half a millennium that freeze has stayed put, and it is only moving with glacial immobility under the present developmental paradigm, which is dominated by foreign images without roots in the African psyche.

We must begin from the beginning. Our children must begin to take it for granted that science is an everyday part of their play, song and existence. Our womenfolk must begin to embrace science as part and parcel of folklore and worklore. And our various publics, whether at the level of the community or the nation-state, must learn to fully integrate science into their enterprises and geopolitical roles.

In making this beginning, we should perhaps be reminded of a perceptive observation that Enrico Cantore, the scientific humanisr, made some 16 years ago in a preface to his book, *Scientific Man*:

'The thesis of this book is that science constitutes an essential factor of the historical development of man as a cultural being... I began to perceive that science is human not only because it is produced by man, but also because it is in itself an agent fashioning man in a culturally new way.' (Cantore, 1977).

So should the latter-day African be science aware, science literate and a science employer. It is then that our 21st-century science-led African world will become holistic in conceptual terms as well as culturally wholesome, within a context of excellence. Centres of excellence have a vital role to play in the achievement of this goal.

CENTRES OF EXCELLENCE

Many African leaders – in government, in training institutions, and in the professions – are seemingly afraid to plan for and establish centres of excellence, even if they talk a great deal about them. They would rather plan for 'centres of specialization', 'regional centres', or some other type of institution than the bold and highly competitive 'centres of excellence'. Africa will need to adopt and utilize systematically and aggressively the notion of centres of excellence in order to create indigenous nuclei of problem-solving capacities which, when twinned with the larger national and regional institutions, would provide an innovative motor for long-range and abiding national and regional development.

Any decisive move in that direction will require a national and regional commitment of a very high order, as a group of senior agricultural scientists concluded at their perspective meeting in Douala, Cameroon, two years ago:

'Polirical will includes the ability to courageously, fundamentally and categorically decide the kind of agriculture we want or the kind of society we want in Africa, both present and future... More political will and commitment is needed to create an environment for freedom, thought and creativity for researchers.' (AAS, 1991).

By 1980, there were well over 400 research institutions in Africa. But they had not maintained the momentum that was evident in the 1950s and 1960s; nor had they provided the high-quality education and relevant research that was desperately required to clear the main blocks to economic and social development. Indeed, the notion of a 'development university' did not establish itself at all in Africa. The attempts by the African university community 'to play a direct, short-term interventionist role in national development', beyond providing a high-level education and professional training, 'to justify its budget and special status in society' were largely unsuccessful (ICIPE, 1991). Rather than the intended partnership between government and university, conflict was generated between the two, as a result of 'idealistic notions of income redistribution and sharing of political power' (ICIPE, 1991).

Yet, the public demand in Africa for education and training, including that at university level, continues to be intense. The dilemma is that, while the continent ought to rely on its human talent to provide the foundation for its relative economic prosperity and social advancement in the long run, the educational infrastructure is so overburdened by numbers and has been made so threadbare by an acute lack of financial resources over the last two decades, that 'the education systems are now not able to foster excellence, nor to reward innovation and achievement'. (ICIPE, 1991).

This unfolding and unrelieved scenario has led to the African nation-states progressively becoming addicted to external solutions, in contrast to the situation in Asia and Latin America. There are now more expatriate scientists, scholars and consultants in Africa than were ever present in the heyday of political independence some three decades ago, and this in effect returns some US$2-3 billion of development aid every year to the North. Enclaves of high-level research have sprung up in the continent since the late 1960s, or have continued to exist since the colonial period, funded largely by international development and aid sources, to seek immediate solutions to particular problems of agricultural production, of health, etc. What these enclaves have not accomplished, parallel to or integrated with their problem-solving objectives, is to develop and nurture the in-country capacity for problem solving. A determined, long-range commitment rapidly to build up and maintain Africa's capacity for science-led development is the single most important task of the continent's leadership in the current decade and beyond.

After receiving his science education at Makerere University College and the University of Cambridge, **THOMAS R. ODHIAMBO** held teaching appointments at University College, Nairobi, before being appointed First Professor of Entomology at the University of Nairobi in 1970. He was made First Director of the International Centre of Insect Physiology and Ecology (ICIPE) in Nairobi, a post he has occupied full time since 1978.

Professor Odhiambo is President of the African Academy of Sciences and Vice-President of the Third World Academy of Sciences, as well as being the holder of fellowships of several national and international academies. His professional interests involve science and technology policy and development issues.

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SOUTH ASIA

Prabhakar J. Lavakare and Kishore Singh

Developments in science and technology in South Asia have their origins in the Indus Valley civilization of around 2500 BC, and there is evidence of the use of scientific knowledge since this period in the fields of town planning, metallurgy, medicine and surgery as well as in areas of pure science such as astronomy and mathematics. The emergence of distinct national boundaries in more recent times has resulted in the new nation states developing their own scientific infrastructures which may perhaps be described as composites of their traditional learning, influences from the colonial era and the need to respond to the very real challenges posed by today's economic conundrums. Contemporary India, with its relative wealth of resources, leads the way in science despite experiencing many of the problems that afflict science and technology (S&T) in the rest of South Asia. It is therefore useful to discuss the degrees of success achieved in S&T in India and to analyse against this background the need for broad-based scientific development in the rest of South Asia.

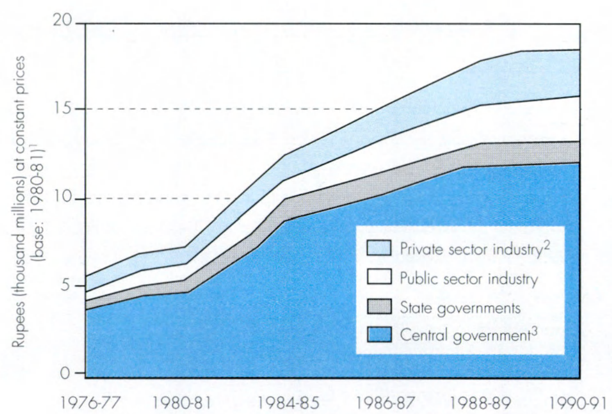
The long tradition of scientific thought was reflected in Indian national planning soon after political independence in 1947, when its first prime minister Pandit Jawaharlal Nehru based the task of nation building on the philosophy of using science (and technology) in development planning. In 1958, he steered the Scientific Policy Resolution (SPR) through parliament – a document still considered the official guide to India's approach to fostering, promoting and sustaining scientific activity in the country. Indeed, the constitution of India has a clause for promoting 'scientific temper' among the people. The present Indian Government has continued to lay emphasis on science and technology. In 1993, a draft paper for a new technology policy focusing on such issues as benefits to society, promotion of environmentally cleaner technologies, promotion of technical skills, linkages with industrial development, etc. is being debated. Science in India thus forms an important item on the agenda for national development.

RESOURCES FOR S&T IN INDIA

Financial resources

In consonance with its philosophy of fostering and promoting science, the government has assumed the major responsibility of supporting S&T activities in the country. Over the years, the national research and development (R&D) expenditure as a percentage of gross national product (GNP) has steadily increased, from 0.18% in 1958-59 to about 1% in 1986-87. The draft for a new technology policy (1993) suggests that by the year 2000 investments in R&D should reach 2% of GNP. The government's planning relies upon the private sector R&D contribution being significantly enhanced, and to achieve this result suitable incentives to industry are envisaged.

FIGURE 1
NATIONAL EXPENDITURE ON R&D BY SECTOR



1. GNP at factor cost is used. For working out constant prices, GNP price deflators as per Economic Survey 1991-92 have been used.
2. The number of units in the private sector varies from year to year.
3. Central government excludes public sector industry.

Source: Department of Science and Technology, Government of India.

Figure 1 shows the dominant contribution made by the central government to the national R&D efforts. During the year 1990-91, its contribution was 68.9% as against that of 23.2% by the private and public sector industries combined. This proportion is in sharp contrast to that seen in developed and technologically advanced countries like the USA and Japan where the industrial R&D sector contributes a significantly larger share.

Human resources

Professor P.C. Mahalanobis, the architect of planning in India, has clearly stated that the 'availability of scientific and technical personnel is an important factor in the economic development and "greatness" of nations however they may be measured...'. The SPR also gives importance to nurturing scientific manpower for the socio-economic development of the country. National surveys of S&T human resources have been carried out every 10 years and the planning commission of the government periodically undertakes exercises to estimate the stock of S&T personnel, as shown in Table 1.

TABLE 1
SCIENCE AND TECHNOLOGY PERSONNEL IN INDIA

Field	Stock of S&T personnel ('000s) 1985	1990	Rate of growth (%)
Engineering degree holders	372.6	454.4	4.0
Engineering diploma holders	564.2	734.8	5.5
Medical graduates[1]	268.2	314.4	3.2
Agricultural graduates	133.3	162.8	4.1
Veterinary graduates	28.3	33.4	3.4
Science graduates[2]	1 419.0	1 684.2	3.5
Science post-graduates	350.3	419.7	3.7
Nursing graduates	3.7	5.5	8.3
Total	3 139.6	3 809.2	

1. Includes dental surgeons.
2. Includes BEd (BSc).

Source: Planning Commission, Government of India

In 1990 the number of scientists and engineers graduating from the university system was around 200 000. However, due to the limited employment opportunities in the country, not all the S&T personnel are gainfully used. Of the total stock of nearly 4 million S&T personnel reported in 1990, only about 300 000 were employed in R&D establishments, and of this number only 7.3% were women.

India has approximately 4.5 scientists, engineers and technicians per 1 000 population, as compared to 184.8 in Canada, 111.1 in Japan and 77.8 in Germany. In a large country like India, if S&T personnel are to play an important role in the development process, not only have their numbers to be increased but so also should their utilization. Several studies are being carried out to establish the size of the brain-drain problem and the measures that need to be taken to reverse it.

THE ORGANIZATION OF SCIENCE IN INDIA

Since support for science in India is mainly from government sources, the organizational structures clearly show the predominance of government departments and government-funded laboratories in guiding the course of science in the country.

Government structures

Over the years 1948-85 fully-fledged government departments were created to deal with atomic energy, space, defence research, electronics, biotechnology, ocean development, industrial research, non-conventional energy resources and environment, as well as autonomous councils for agricultural and medical research. Most of them benefited from having scientists as their chief executives. In order to provide a policy-coordinating role for various activities in S&T, a separate department of science and technology was set up in 1971. The government has also set up, from time to time, scientific advisory committees to the cabinet and to the prime minister. The National Committee on Science and Technology, set up in 1971, made its major contribution when, in 1973, it prepared a Science and Technology Plan (1974-79) which provided, for the first time, a strategy for integrating S&T in the socio-economic development of the country. The plan did provide a very rational approach to development but even today its effective implementation is facing organizational and managerial problems. The S&T sector is still operating in considerable isolation, except for areas like agriculture and space science which have set very good examples for the application of S&T to the overall socio-economic development of the country and should perhaps be followed by other scientific agencies.

Industrial R&D

As stated earlier, industrial R&D activities represented approximately 23% of the total national investment in R&D during 1990-91. On 1 April 1990, there were 1 138 industrial sector R&D units (in both private and public sectors) employing more than 60 000 personnel. The average per-unit industrial R&D expenditure classified by sector is shown in Table 2.

TABLE 2
PER-UNIT INDUSTRIAL R&D EXPENDITURE IN INDIA CLASSIFIED BY SECTOR, 1990-91

	Per-unit R&D expenditure (Rupees '00 000s)		
Industry group	Public sector industry	Private sector industry	Total industrial sector
Defence industries	1 621.3	–	1 621.3
Fuels	707.8	22.7	365.3
Fertilizers	274.8	125.0	194.1
Transportation	58.7	163.5	152.6
Rubber goods	28.9	120.6	115.8
Metallurgical industries	274.0	34.0	101.8
Telecommunication	295.0	17.3	96.7
Electronics & electrical equipment	244.3	44.6	72.4
Drugs & pharmaceuticals	82.7	70.2	71.1
Food processing industries	8.0	68.5	66.7
Industrial machinery	14.2	49.4	45.9
Chemicals (other than fertilizers)	140.3	34.9	40.1
Other groups	107.9	46.1	52.8
Total	286.5	52.2	84.1

Note: A unit is an institution carrying out R&D. As at 1 April 1990, there were 1 138 industrial sector R&D units.

Source. Department of Science and Technology, Government of India.

Under the recently proposed policies of the government, the industrial R&D sector will be encouraged to enhance its contribution to the national R&D effort. With the recently introduced economic liberalization, the industrial sector will encounter much greater competition than in the past and it is expected that, in the face of market forces, a greater reliance on indigenous R&D efforts will become necessary. But, on the other hand, the shift towards a more open economy is likely to facilitate the import of technologies which, together with the entry to the local market of multinational companies with collaborative arrangements, may prove to be a damper for indigenous R&D efforts.

Education sector

The organization of R&D activities in the education sector is more or less unplanned and very marginal, though some excellent basic research groups have developed in a few educational institutions. Research activities in these institutions are supported primarily through fixed-term research grants which are awarded to a relatively small number of active researchers. There were 180 universities registered in 1990-91 as compared to only 27 in 1950-51. The quality of research in several universities is still somewhat inferior, perhaps due to the fact that the facilities in many of these institutions are inadequate. Over the last 5-10 years, however, several governmental schemes and research projects have selectively improved the infrastructure and therefore the quality of research in a few universities.

State level organizations

During the last 10 years or so, there has been a concentrated effort to set up appropriate S&T planning infrastructures in the 25 states of the country. State-level S&T councils are expected to use the results of national R&D efforts to ensure that socio-economic benefits accrue to the people of the states through the effective application of science and technology to the problems of development. This approach needs to be strengthened.

The overall organizational structure for S&T has perhaps grown too large; not in terms of investment but in terms of coordination and management. The administrative machinery needs to be considerably streamlined and geared to respond more rapidly. Quality and selectivity should be very strictly adhered to, if excellence in science is to be the immediate goal for India.

RESULTS

The commitment of the government to use S&T for national development has borne fruit in several areas such as agriculture, health, surveying resources, communications, education, defence and power production.

Notwithstanding the increasing population, the country is self sufficient in food – thanks to scientific input from agricultural research. The vastness of the country is now thoroughly networked by a national satellite-based telecommunication service. Space technology is also being used for surveying national resources and weather forecasting, very important areas for a predominantly agricultural society. Improved health services, though far from ideal, have reduced the death rate from 27.4 per 1 000 in 1950 to 11.9 in 1985 and the corresponding life expectancy at birth has increased from 32 to 56 years. Increased generation of electrical power and the electrification of villages have been important benefits of the application of S&T. Using modern mass media techniques and through the efforts of field groups, the literacy rate has been stepped up to more than 50%, and a target of 100% for the age group 15-35 years is expected to be achieved through a technology mission approach. In spite of these positive developments, the potential of science has yet to be fully exploited. Scientific activity needs to be further strengthened, and innovative and efficient managerial input is required for integrated socio-economic development through S&T, with closer links between the producers of science, the users of science and its ultimate beneficiaries – the people of India.

THE ORGANIZATION OF S&T IN SOUTH ASIA

In comparison with the situation in India, the development of S&T in the rest of South Asia is faced with more complex problems. With very low per capita incomes and literacy rates (on average around US$290 and 40% respectively, except in Sri Lanka where the per capita income and literacy rate is well above the regional average) the region lags behind most other developing countries. Some countries, such as Bhutan and the Maldives, even lack a third-level education system.

Policy in these countries (as in other developing countries) invariably recognizes the role of S&T in development planning, a feature that is reflected in the Sixth Plan (1983-88) of Pakistan, the Seventh Plan (1985-90) of Nepal, the Sixth Plan (1983-87) of Sri Lanka, the Third Plan (1986-90) of Bangladesh, and the Sixth Plan (1986-91) of Bhutan. The high priority attached to S&T is indicated by the fact that the direction and coordination of S&T development is entrusted to top-level government bodies, constituted for this purpose. The National Committee for Science and Technology in Bangladesh is the focal point for all S&T related decisions, while the National Council of Science and Technology orients and supervises overall science policy; the Royal Nepal Academy for Science and Technology promotes S&T development under royal patronage; the Natural Resources, Energy and Science Authority in Sri Lanka advises the President on S&T development policies, plans and programmes; and the Pakistan Council for Science and Technology coordinates plans and programmes in S&T.

INSTITUTIONAL INFRASTRUCTURE FOR S&T

In national endeavours for developing S&T, prime importance has been given to the creation of S&T institutional infrastructure; scientific R&D institutions, competent in an array of disciplines, have been established, mainly under the umbrella of councils for scientific and industrial research. PCSIR in Pakistan has nine laboratories including three which are multifunctional; BCSIR in Bangladesh has three laboratories; CISIR in Sri Lanka has several laboratories; Nepal has the Research Centre for Applied Science and Technology (RECAST) as part of Tribhuvan University, and four other autonomous institutes. There are also a number of other institutions in the region for research in agricultural and medical sciences and other socio-economic development areas.

In parallel, institutions of higher education for generating S&T personnel constitute another component of the institutional infrastructure.

Besides 53 research institutions, Pakistan possesses 23 universities including four engineering universities and three agricultural universities, 170 polytechnic and vocational training institutes and 101 professional colleges. In addition to 20 major research institutions, Sri Lanka has nine universities, 24 technical colleges under the governance of the Ministry of Higher Education including eight polytechnics, 12 junior technical institutes, three agricultural schools and a number of specialized training institutes established by government agencies.

Apart from 18 research institutes in Bangladesh, there are four engineering colleges, nine polytechnics and 54 vocational training institutes. Bangladesh is also setting up an S&T university.

Nepal maintains, besides RECAST, four other research centres at the Tribhuvan University (which is responsible for all higher education in the country) and four auronomous institutes for technical education and research.

Though not yet endowed with a third-level education system, Bhutan has established some polytechnic and technical institutes such as the National Institute of Forestry, the Integrated Agricultural Training and Research Centre and the National Veterinary Institute. The Maldives too have no facilities for third-level education but possess two technical second-level educational institutes.

RESOURCES FOR S&T IN SOUTH ASIA

A perusal of policy declarations on S&T in the countries of South Asia shows that the majority of socio-economic problems and development tasks, covering an ambitious range of priority areas, are becoming the responsibility of the S&T sector. S&T policies in the countries of the region commonly underline the need for:

- developing technological capabilities including, in some cases, new, advanced technologies as an integral part of the national strategy for self-reliant growth;
- generating personnel with the required specialized skills;
- acquiring technologies, their adaptation and further development;
- the more effective application of local technologies;
- promoting and disseminating S&T and the widespread application of S&T for socio-economic development.

Demanding as these objectives are, their realization would be possible were they not impeded by severe S&T resource limitations. National R&D expenditure in the countries of the region – including foreign grants under development cooperation and expenditure on the social sciences – is less than 0.5% of GNP. Indeed in the mid-1980s, it was an abysmally low 0.3% of GNP in Bangladesh, Nepal and Pakistan. Regrettably, the resources devoted to S&T as a whole are only slightly higher than the national R&D expenditure.

In spite of policy declarations that S&T needs to be geared to solving developmental problems, R&D is generally biased in favour of the basic sciences rather than the applied sciences and the bulk of R&D expenditure goes towards routine administrative matters. Furthermore, a tendency to undertake too many projects results in the R&D effort being fragmenred.

Private sector industrial R&D is practically non-existent in the countries of the region. Its share in the national R&D in Sri Lanka was 7% in 1985, and the situation in the rest of the region is even worse.

There is a general shortage of qualified personnel for S&T development in the countries of the region owing to a very low percentage of the population being enrolled in third-level education, but it is especially acute as regards R&D personnel. In Pakistan the number of R&D personnel was around 6 000 (1988-89), in an environment of slow growth of S&T manpower. In Sri Lanka, R&D personnel in the mid-1980s was less than 3 000 scientists and engineers. In Nepal, the number of S&T personnel presently engaged in R&D amounts to 334 scientists and engineers and only 75 technicians. Bhutan had only 17 engineers (1987), leaving the country dependent on foreign personnel and assistance in the form of overseas training for technical personnel.

The shortage of technical manpower – there are generally more engineers than technicians – is due to the fact that second-level technical enrolment is extremely low, being about 1.6% of overall second-level enrolment. The orientation of the higher education system, as it has evolved, has been to produce more scientists and engineers for S&T institutions and for the formal industrial sector (mostly public) rather than the technicians necessary for the small-scale and informal sector, which forms the bulk of the economic activities in the countries of the region.

INDUSTRIALIZATION OF RESEARCH

Performance indicators of scientific research as measured in terms of inventive activity, therefore, present a rather dismal scenario: only 15 patented processes and 15 industrial designs between the enactment of patent laws in Nepal in 1965 and 1982-83; less than 200 patents applied for annually on average in Bangladesh and Sri Lanka. There are 400-500 patent applications in Pakistan annually on average, but the majority of these are foreign owned. Industrialization of research remains highly limited; few of the processes developed by R&D institutions go into production.

Only a small number of the processes released from PCSIR have been commercialized – in fact less than 100 by 1985. In Sri Lanka, only two of 19 R&D projects undertaken by CISIR and only three of 36 projects undertaken by the National Engineering Research and Development Centre had gone into commercial production during the period 1982-87. In Bangladesh, from the creation of BCSIR until 1985, only about 180 patented processes had been developed of which 106 were leased out, and around a mere 20 had actually gone into production.

The drawbacks to effective S&T delivery in the region emanate mainly from:

- a lack of viability in the projects undertaken;
- weak linkages of R&D institutions with industry, a shortcoming which is reflected in the lack of commissioned or contract research and which inhibits possible contributions from the S&T sector;
- a lack of specialized services for industrial liaison and technical assistance, and weak engineering capabilities in the R&D institutions;
- a lack of venture capital for covering the risks inherent in technology innovation;
- poor management of R&D institutions which tend to be run as government departments rather than being managed in a corporate spirit.

A major constraint on S&T is that due to policy concentration on R&D as an input activity, technology innovation receives only marginal resources and efforts. Little R&D work is undertaken beyond technology generation or, at best, the inventive stage, whereas the need for investment in product development, as the experience of Pakistan as well as of India shows, is nearly 10 times greater. In fact, policy concern with R&D diminishes as one gets closer to the market.

SCIENCE TEACHING AND RESEARCH IN SOUTH ASIA

The system of higher technical education is even more isolated from the productive sector than the R&D institutions. Research in the universities is frequently too academic, lacking adequate financial support, and sometimes quality and relevance. The higher education system does not closely interact with the industrial and commercial sectors, which are in fact badly in need of S&T input.

- In Pakistan, the deficiency in R&D personnel is attributed to a comparative deterioration of standards of teaching and research at universities, and a diminishing emphasis on research. According to a survey by the Pakistan commission on S&T, less than 25% of scientific manpower in the universities is engaged in research work.
- In Sri Lanka, a negligible amount – on average less than 0.25% – of the capital grant for education is spent on research.
- Recurrent expenditure on research and publication in Tribhuvan University, Nepal, was 1.3% of its budget for 1988-89.
- Unplanned expansion of higher education, having little relation to market demand, as in Bangladesh, has resulted in a mismatch between the outflows from various levels of technical education and the demands of the labour market.

A fundamental requirement of higher technical education is to be more responsive to the world of work, rather than to produce graduates in the classical mould. This calls for well-considered measures towards curriculum development so as to cater better for socio-economic needs in vital areas such as food and agriculture, irrigation and water resources, energy, health care, the service sector, technology and environment, etc. and to bring science teaching in higher educational institutions in conventional disciplines into alignment with the rapid advances taking place in S&T.

Vocational education has been a casualty of development; a critical shortage of trained teachers and quality equipment, and highly inadequate practical work facilities, are problems evident throughout the region. It does not place the requisite emphasis on upgrading traditional skills, nor does it focus on enhancing its relevance and utility for small-scale and rural development programmes.

SOME MAJOR TRENDS

Market economy and technology acquisition

The trend towards a market economy and privatization is becoming all-pervasive in South Asia and is creating a new, different environment for scientific research. It is impelling R&D institutions to be more competitive and productive, and to orient themselves towards a demand-led approach. S&T policies are already taking into greater consideration the need to create a propitious environment and to provide mechanisms for attracting foreign investment and technology.

Institutional mechanisms for technology transfer

In order to deal better with the problems faced in technology transfer, new institutional mechanisms are being created. Thus, Pakistan has recently created a national centre for technology transfer, to serve as a focal point for technology transfer and development. Bangladesh and Nepal are also contemplating creating such centres.

Pakistan has also created a new agency, the Scientific & Technological Development Corporation, as a subsidiary of PCSIR, for promoting innovation and more effective development and transfer of indigenously developed processes.

Research-industry linkage

The trend towards a market economy has a direct bearing on linkages between research and industry. Private industrial R&D is being promoted in Pakistan by encouraging the creation of R&D centres in industrial establishments. The private sector is also being increasingly recognized as the principal avenue towards development. In Nepal, industry participation in technology development by inhouse R&D and collaborative research is being promoted. In fact, the Institute of Engineering derives 10-20% of its resources from consultancy services. Sri Lanka's Industrial Policy Statement of 1987 underscores the need to create conditions that stimulate demand for technology and to orient R&D institutions to provide access to demand-led technologies.

Privatization and its impact on higher technical education

As the experience of Sri Lanka shows, lasting benefits from liberalization in terms of human skills development and technological capabilities are likely to be minimal unless conscious and deliberate policies are adopted to optimize these benefits. Privatization programmes, for instance, in Bangladesh, are hindered by a shortage of resources – technical, financial and human. Privatization is therefore having its impact on S&T by making demands upon the hitherto public domain of higher technical education.

National requirements in basic sciences and technical training

Because of rapid advances in S&T, strengthening university basic science education by training and retraining teachers has become a matter of necessity for all developing countries. The need for strong science and mathematics programmes is recognized in Pakistan and Bangladesh and special importance is attached in Pakistan to training engineers. Training specialists in the basic sciences is becoming a growing policy concern in Bangladesh as well as in Nepal. Bangladesh has recently introduced biochemistry teaching, and the establishment of a national biotechnology research centre is proposed.

Science teaching in schools in the least developed countries is poor, its primary requirement being to 'extend S&T training among those at school age'. In an attempt to meet this objective, UNESCO is promoting a technical curriculum cell at the Vocational Training Centre in Male in the Maldives for promoting technician education programmes. In view of the high priority being placed on industrial development, Bhutan too is giving a new dimension to scientific education and technical personnel training; the national education policy is being revised so that it places more emphasis on scientific and technical education.

S&T programmes in new advanced technologies

Advances in S&T are dramatically changing the relationship between science, technology and economic development, and the South Asian region is making an effort to participate in these growth areas. R&D institutes have been established in Pakistan in the fields of electronics, oceanography and silicon technology, and institutions specializing in fields like biotechnology and genetic engineering are in the process of being set up. Renewable energy, materials science, lasers, fibre optics, etc. are also becoming priority areas. Additionally, Pakistan has launched a programme for specialized training abroad, under which 100 scientists have already been trained. Similarly, Sri Lanka's policy regarding capacity creation in high technology seems relatively focused with centres of excellence like the Institute of Fundamental Studies, the Computer and Information Technology Council and the Sri Lanka Centre of Modern Technologies. In the national S&T policy of Bangladesh (formulated in 1980) support for emerging technologies like biotechnology, genetic engineering, microelectronics, new and renewable sources of energy, etc. has been considered essential. The S&T policy of Nepal, finalized in the late 1980s, stipulates that the country's R&D programme should aim at developing the capability to utilize modern sciences like biotechnology as far as practicable. Bhutan, which considers science-based technologies necessary for the improvement of the living standards of its people, also lays emphasis on the adoption of those emerging technologies, such as microelectronics, renewable energy sources and biotechnology, which are directly relevant to its socio-economic conditions, and on the need for ensuring a suitable blend of these with traditional technologies.

Current trends towards market economies and research-industry collaboration may introduce a new S&T perspective in the South Asian region, and the balance between the culture of administration and science may undergo a shift towards less administration and more science. Concern with new advanced technologies would also imply more policy attention to technology innovation. Activities being undertaken for inculcating and promoting science, and its widespread application in socio-economic development by mobilizing the creative energies in the region, may also give a new dimension to the science-society interface, causing contemporary S&T to permeate the regional cultures in a more profound manner.

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P.J. LAVAKARE is Executive Director of the United States Educational Foundation in India and Emeritus Scientist of the Council for Scientific and Industrial Research in New Delhi.

A physicist by training, Dr Lavakare worked for many years as a research scientist at the Tata Institute of Fundamental Research in Bombay and the University of New Hampshire. Later he was appointed Science Administrator at the Electronics Commission and then at the Department of Science and Technology in New Delhi. During this time Dr Lavakare also served as Secretary to the Science Advisory Council to the Prime Minister of India and Honorary Science and Technology Adviser to the Planning Commission of the Government of India.

KISHORE SINGH, who was responsible for the sections in this chapter dealing with South Asia, is a member of the International Council for Science Policy Studies and has worked for over 10 years as a consultant expert to UN agencies in the areas of S&T development policies and technology transfer.

Dr Singh received his postgraduate training at the University of Paris I and has taught doctoral courses in technology transfer at the University of Paris V. He was recently visiting professor at the University of Roskilde, Denmark.

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CHINA

Shen Chenru and Zhang Shaozong

Reform is the major theme in China today. Change is being witnessed in every sphere of activity with the most profound reforms taking place in the nation's economy. Because the potential of science and technology (S&T) as a productive force is generally recognized, the reform programme is giving this sector increasing emphasis, although basic research, for the most part, is still the concern of the scientific community alone since it is perceived as having no relation to production. Much of the public have yet to understand the potential value of basic research; in their eyes basic researchers are academically inclined people with little practical ability. By contrast, technicians enjoy a much better public image.

This article describes briefly the overall state of basic research in China, introduces the Chinese Academy of Sciences (CAS) which is the largest centre of basic research in the nation, and illustrates the projection of China's traditional culture into her science and technology.

THE POSITION OF BASIC RESEARCH

The concept of basic research is interpreted variously from country to country. In China S&T are generally made up of three types. The first type consists of forms of research and development (R&D) which will directly serve the effort to double the gross national product (GNP) by the end of the century and is therefore the main area of S&T activity. The second includes R&D in new and high technologies with the aim of developing and establishing new high technology industries. Basic research is at the third type; its mission is to understand natural phenomena systematically and rationally in order to provide new concepts, theories and methods for explaining nature. Basic research is in turn divided into three classes. The first class is orientational basic research with an applied background, the second is accumulative basic work with the aim of collecting original material and data, and the third is pure basic research. Traditionally, pure basic research has meant theoretical inquiry in mathematics, physics and chemistry while astronomy, geoscience and biology belong to the second class.

MANAGEMENT FRAMEWORK

China's S&T system consists of the CAS, universities and institutes of the state ministries and commissions. The State Science and Technology Commission (SSTC) is in charge of coordinating this system. Originally the system was designed according to an economic plan under which most S&T projecrs were assigned and funded by the central government. The research units undertaking these were accountable only to the state. The defects of this system, especially at the third level, are obvious, because of its weak relation to the productive sectors. With the introduction of market mechanisms during the past 10 years or so, many aspects of the system have changed, but not its essential character. Clearly, fundamental change in the research system will depend upon the overall development of a market economy, and China is only just beginning to take legislative steps towards liberalization.

In the past the annual state expenditure on S&T was small, amounting on average to about 1% of GNP, while the funding for basic research consisted of only 4.8% of this amount. Both these investment quotients were below the world average.

The National Natural Science Foundation (NNSF), which was established in 1986, has taken what can be considered the first steps towards reforming China's S&T system by diversifying funding. Since then a number of state ministries and productive sectors have successfully established their own R&D foundations and so the first and second levels of S&T have received unprecedented support. By comparison, basic research appears to have been ignored by the NNSF; its status within China's S&T policy framework is therefore evident from the degree of funding it receives.

As a result of efforts to liberalize the economy, a private S&T sector which is independent of the state management framework is emerging in southeast China, particularly in the special economic zones of Shenzhen, Zhuhai, Shamen, Wunzhou and Ningpe. This sector is market-oriented, directly linked to production and is much more flexible and active than the state-owned science establishment. Because of the much higher wages it offers, it is attracting increasing numbers of S&T professionals from the state-owned sectors, including prestigious academic institutes and universities. The future of this private S&T sector will depend on whether the reform programme is pursued without interruption.

THE CURRENT SITUATION

Although S&T is managed according to the classification mentioned above, statistics that correspond to this clustering have yet to be produced, and it is therefore difficult to describe China's basic research accurately. However, information can be derived from a report entitled *Investigation of the National Basic Research Disciplines of the Natural Sciences (INBRDNS)* which was commissioned by the CAS under a mandate from the SSTC. This report, which was contributed to by more than 100 specialists from the CAS and other institutions, was prepared following an investigation from July to December 1987, and consists of sub-reports in 15 disciplines which include mathematics, physics, chemistry, astronomy, earth sciences, biology, basic agronomy, basic medical science, energy source science, photoelectric science and engineering science. *INBRDNS* is the first authoritative investigation into China's basic research, although it contains insufficient statistics.

INBRDNS declares that China has established a large basic research structure covering many disciplines at the most basic level and that it has made significant contributions to the nation's economic development, defence and science, as well as to Chinese self-respect and self-confidence. The most outstanding examples of the science establishment's strength are the successful development of China's own A-bomb, H-Bomb and satellites. The report also lists scientists who have made individual or cooperative contributions which are acknowledged worldwide and points out that Chinese surveys and explorations in the fields of geology, geography, seismology, pedology, meteorology, ecology, zoology and botany have helped us to better understand our planet .

However the basic research structure is described as weak and of low efficiency. In basic mathematics, for example, *INBRDNS* pointed out that China's overall level remains far behind that of the developed countries and in several important fields has fallen behind India and Brazil. Of the approximately 20 000 members of the Chinese Mathematical Society only several thousand are engaged in basic research. According to this Society's statistics for 1985 only about 400 Chinese mathematicians produced more than two papers which were translated and published in international mathematical journals; by contrast, of the 14 000 members of the American Mathematical Society more than 4 000 published two or more papers – 10 times as many as in China.

A similar analysis was made in *INBRDNS* with regard to chemistry. According to the statistics from a survey of 15 institutions including the CAS and 11 key universities under the governance of the State Education Commission (SED), in 1983 and 1984 personnel engaged in chemical research numbered 10 000 of whom 6 500 were in the CAS and 3 000 were in the universities. Of this last number 700 were graduate students. It was estimated that about 60% of the 10 000 chemistry professionals (6 000 people) were engaged in basic research. According to data in *Chemical Abstracts*, more than 380 000 papers and 4 700 books on chemistry were published and 73 000 chemistry-related patents were granted in 1985, amounting to a total world output in chemistry of about 460 000 items. The USA led this production with a 27% contribution, while the USSR and Japan contributed 14.9% and 11.3% respectively. The Federal Republic of Germany, the UK, France, India and Canada followed. China ranked ninth, accounting for 2.6%. Chemistry professionals in China produced 11 906 papers in 1985, of which 10 532 were published in Chinese while the rest were in foreign languages. *INBRDNS* pointed out that there was a large gap in achievement in chemistry between the three leading countries and China.

In assessing the overall academic level of biology, *INBRDNS* clearly indicated that China's molecular biology is, in general, not comparable to that of a middle-sized state in the USA in terms of either the number of researchers or the quantity and quality of papers published annually; it is in fact five to 10 years behind the developed countries and led by developing countries such as India and some in South America. In taxonomy, which is a branch of biology categorized in the second class of basic research, Chinese progress has been modest. China has many more indigenous insect varieties than the USA and the former USSR, but while these two countries have identified more than 85 000 and 50 000 varieties respectively, China has only identified 15 000. On the other hand *Chinese Flora*

(Flora Sinica), a compilation expected to consist of 80 volumes, has been produced steadily since 1959, with its 65th volume being published in 1992. Yet it is being issued almost a century after the publication of *The Flora of British India* (1872-97). The Chinese Society of Ornithology has 360 members, of whom 83 are qualified ornithologists, while Japan's Society of Ornithology boasts 1 000 members. Similarly, China has 400 professionals engaged in insect classification research as against the USA's 2 000.

The successful completion in 1988 of the Beijing Electron Positron Collider (BEPC) was a significant achievement in the field of high-energy physics, but *INBRDNS* pointed out that some disciplines such as condensed matter physics, optical physics, and atomic and molecular physics are relatively weak. Basing its conclusions on statistics from the NNSF, the report warned that the number of physics research groups producing outstanding work has been declining in recent years.

It is a matter of concern that China's basic research is deficient in creativity and innovation, with most studies imitating pioneering work that is done overseas. Some studies are conducted merely to fill a gap in the basic science research programme and demonstrate little vitality of their own. There is also considerable duplication of effort. For example, there are no less than 50 institutes of geology under the purview of the state ministries, the CAS and the provinces and their research areas frequently overlap. A sharp increase in the number of research units took place in the late 1970s and the early 1980s, increasing the number of institutes of the CAS from 64 to 119. Universities and the industrial sector have also established their own research centres introducing an element of competition.

A problem highlighted in *INBRDNS* is the shortage of research funds. According to a survey of research allocations for biology in 1986, the average funding per topic was 28 800 yuan (in 1986 there were approximately 3.45 yuan per US$) for the institutions of the CAS, 16 000 yuan for other institutions of higher learning and 7 600 yuan for local institutes. To put these amounts into perspective it should be borne in mind that the last-mentioned figure was equal at that time to the cost of two television sets. In the 1980s the total basic research funds allocated to universities was on average 100 million yuan a year. Average funding per topic, however, decreased from 43 000 yuan in 1983 to 29 300 yuan in 1987. Funding for mathematics was lower than the average, at 8 000 yuan per topic.

Another serious problem facing the Chinese science establishment is that the basic research workforce is relatively advanced in age. The dearth of younger scientists, the consequences of which are becoming increasingly apparent, is attributed to the political turmoil between 1966 and 1976, which deprived a generation of scientific education and training.

CHOICES

Clearly, China's basic research structure is failing to meet the nation's social, political, economic and cultural developmental needs. Reform is therefore inevitable; a decrease in scale and an increase in input are needed.

Most Chinese analysts usually stress the unsuitability of the basic research structure to the national economy. As far as the shortage of funds is concerned, discontent in this respect is common, even among researchers in developed countries who enjoy significant sponsorship by the private sector and wealthy individuals. It is also noteworthy that, historically, basic research has been largely undertaken by people who are driven by intellectual curiosity rather than a desire for fame and fortune. Even if China's S&T budget increases from about 1% of GNP to 1.5% or 1.8%, and the share for basic research from 4.8% to 10-15% of the total S&T input, as has been proposed by some scientists, there will still be calls for increased input because, like education, basic research is essentially a cultural need. Therefore a link must be maintained between basic research and culture and, although state funding is imperative, the research community should not depend on the central government alone; it should seek support from the whole of society including the private sector.

EFFORTS

In recent years the SSTC has made a significant effort to reform China's S&T system. The Spark Programme, the Torch Programme and the '863' Programme designed by the SSTC have all been implemented since the seventh Five-Year Plan. The Spark Programme has aimed to change the backwardness of the remote and poor areas of the country through S&T, the Torch Programme to develop new and high-technology industries at the local level and the '863' Programme to develop high technologies. These Programmes have been given considerable economic support and have promoted China's S&T system to the main arena of activity.

In order to stabilize basic research, the central government is also making every effort to increase the input to this area; the total investment for 1993 will exceed 300 million yuan. Moreover, investment will increase by 70 million yuan per year in 1994 and 1995.

In 1992, the SSTC launched the Climb Programme as a state-level effort to refine China's basic research. This programme includes 30 projects selecred by the SSTC's foremost specialists from fields in which China's present capability would enable her to make breakthroughs and hold a position of superiority in the near future. During the eighth Five-Year Plan, the annual input for each of these projects is 1 million yuan, much more than that for a conventional project. Moreover, 77 key state laboratories were established during the seventh Five-Year Plan and the creation of a similar number of additional laboratories is envisaged. The total input for all these laboratories is estimated at about 1 million yuan. Despite these efforts, China's basic research has yet to demonstrate vigour, and many basic researchers remain reluctant to leave their original posts.

THE CHINESE ACADEMY OF SCIENCES

Brief history and scale

The Chinese Academy of Sciences (CAS) is the largest and most comprehensive centre for the natural sciences in China. The aims of the Academy are to develop new concepts, theories and methods in the natural sciences, to solve key social and economic development problems and to train scientists and technicians. For more than 40 years the CAS has made important contributions to China's economic growth and scientific development, and according to preliminary statistics for 1989, more than 900 of the Academy's research projects won state-level awards that year.

The CAS was founded on 1 November 1949 by the merging of two predecessor institutions, the Central Academy of Sciences and the Peiping Academy of Sciences. In the early days, the Academy had only 21 institutes and about 300 professionals. By the end of 1989 it consisted of 121 institutes and nearly 90 000 staff of whom researchers and technicians numbered about 56 000 (Tables 1, 2 and 3). These institutes are distributed in 21 provinces, municipalities and autonomous regions. The Academy has established branches in 12 major cities. In addition, it has six Academic Divisions: one each for the disciplines of mathematics and physics, chemistry, earth sciences and biology, and two Divisions of Technological Sciences. The Academic Division members are eminent scientists and technologists selected from within the CAS and other institutions and they enjoy the highest honour in China. The membership of the Academic Divisions numbered 400 in the past but 200 new members were selected in 1992 when the General Assembly of the Academic Divisions, which is considered the highest consultative agency for S&T in China, met for its sixth session in Beijing.

Reform – a timescale

The general deficiencies that afflict China's S&T system have also existed in the CAS. Moreover, with the increasing number of research institutes affiliated to universities and the industrial sector, the Academy is losing the high status it enjoyed in the past. Universities have superior education systems while the industrial sector is stimulated directly by economic forces. The reform of the CAS is therefore imperative under present circumstances, since its pre-eminence is being threatened. At the same time the central government has stipulated that the Academy must shift the focus of its efforts towards the main areas of S&T activity. In other words, its basic research must be reduced. The Academy's leadership has therefore established a reform policy envisaging a shift towards R&D with a limited but goal-oriented basic research structure that is open to the entire country and indeed to the whole world.

In 1981, a new allocation mode was introduced.

TABLE 1
INSTITUTIONS OF THE CHINESE ACADEMY OF SCIENCES, 1985

Category	Number
Research institutes	121
Institutes of policy and management	1
Institutes of history and natural science	1
Universities of science and technology of China, including graduate school	1
Beijing College of Managerial Cadres	1
Factories	9
Books and publications	7
Other	29
Total	170

TABLE 2
PERMANENT STAFF OF THE CHINESE ACADEMY OF SCIENCES CLASSIFIED BY FUNCTION, 1985

Function	%
Basic R&D and teaching	45.2
Technicians in other fields	11.9
Auxiliary	1.8
Workers in institutes	11.2
Workers in factories and laboratories	19.9
Administrative cadres	10.0

TABLE 3
PERMANENT STAFF OF THE CHINESE ACADEMY OF SCIENCES CLASSIFIED BY DEPARTMENT, 1985

Department	%
Research institutes	82.6
Education and training	4.6
S&T service	8.1
Administration	4.7

Average allocations to departments were reduced while support to research projects selected by peer-review and competition was enhanced. Thus a classified management of research projects was implemented with a funding ratio of 4:3:3 for R&D, public welfare-oriented S&T and basic research respectively. In the same year the CAS established its Science Foundation which is for the benefit of the whole country. In 1986 the Academy supported 655 selected basic research projects with 35 million yuan while its Science Foundation provided 172 million yuan in support of 4 424 research projects throughout the country. It was also in 1986 that the NNSF was established, with the intention that it would function independently of the CAS in a manner similar to the Academy's Science Foundation.

In 1984 there was a proposition to do away with the science establishment's inward-looking policy and to create research laboratories which were more open to cooperation, mobility of scientists and internationality. As a result, in 1985 the formal creation of the first 'open' scientific institutions was announced, consisting of two institutes and 17 laboratories. By 1990 a further 63 such laboratories, two institutes and eight field test stations were opened.

In 1984 the CAS had also decided to aim at developing high-technology products in order to achieve the nation's economic goals, and by 1989 more than 7 000 scientists and technicians had left their research laboratories to enter these 'high-tech' enterprises.

In 1987 the President of the CAS presented a reform policy which aimed to mobilize the main strength of the Academy towards directly serving the national economy while maintaining an academically refined contingent engaged in basic research and high-technology projects. In March of the following year, the President presented the concept of 'one Academy, two systems', indicating that two distinct systems would co-exist within the framework of the CAS: a scientific research system and a high-tech development system. This concept met with unequivocal support and has led to the proposition by a number of noteworthy scientists that a Chinese Academy of Technology be set up.

In early 1993 the Academy's President further defined the 1987 policy of rebuilding the CAS by presenting a two-layered model for its future structure. The Academy would consist of a core of a small number of science centres and technology centres which would be research institutes with international academic standards. An external layer would be constituted of a number of profitable and efficient high-tech enterprises which are independent corporations established by, and intimately connected with the CAS and its institutes. Basic research should be refined and concentrated in a few fields. Work in these fields should not only be at the frontiers of international scientific inquiry but should also be of strategic relevance to the nation's long-term economic development.

Recent information indicates that the proposed Chinese Academy of Technology (CAT) is soon to be established. If the CAT's S&T personnel is to be drawn partly from the CAS and partly from the state ministries and commissions, then the 'one CAS, two systems' concept will be further developed, and the running debate as to whether a large academy such as the present CAS is preferable to a small academy concentrating on basic research will finally be resolved.

The reform of the CAS with its 90 000 staff in 170 units is an immensely difficult undertaking, not least because the Academy's scientists and technicians cannot easily overcome habits formed in a planned economy. But the leverage of the market economy is slowly being felt, the CAS's basic researchers are experiencing economic difficulties and, because the Climb Programme can never accommodate all of the Academy's researchers, most of them must seek other fields.

SCIENCE AND THE TRADITIONAL CULTURE OF CHINA

The traditional culture of China is compatible with contemporary science and Chinese people experience no cultural barriers in accepting science. In China, ancestry worship is practised rather than religious worship, and cultural symbols such as Confucius and Lao Zi never rejected science but attempted to accommodate it. In fact, a recent opinion survey conducted by the Chinese Society of Science and Technology revealed that more than 70% of the public were in favour of science.

A requirement in understanding Chinese culture is the acceptance of the fact that two tenets have dominated Chinese thinking. The first of these is Sinocentrism; the word 'China' means central state or nation. This indicates how the Chinese perceive their country. Sinocentrism has been part of Chinese culture since the 11th century BC, and it is only since the 17th century that this mentality has been challenged by Western culture, of which modern science is a part. Since then, the Chinese, as a nation, have been defensive and have felt that their glorious culture had become a heavy burden. Sinocentrism transcends ideology and political institutions and pervades all fields. It is this cultural mentality which has induced an over-anxiety for quick results in China's development. Its manifestation in S&T is apparent in the magnitude of the basic research undertaking and the attempts to recruit staff in the effort to realize the objectives described earlier.

The second tenet that has characterized Chinese culture is its integrated view of the universe. Nature is perceived as a whole and all its entities, be they the individual, a population or all of humankind, are considered integral parts of the environment. This cultural predisposition prevented the emergence of science in ancient China because scientific thought requires detached observation. For example, although logic and geometry emerged in China at the time of Confucius, these disciplines did not develop in a way comparable to Aristotelian logic and Euclidian geometry. The ability of the ancient Chinese was manifested mainly in technology and art. In contemporary science, Chinese researchers have proved themselves capable problem solvers but appear to be deficient in their ability to identify problems. This lack of creativity and new ideas in basic research may thus be attributed to the inculcated integral perception of nature. On the other hand, many of the problems facing the world as a whole, such as environmental pollution, global warming and stratospheric ozone depletion, require an integrated approach. Moreover, advancements in computer science have made such approaches possible.

The rapid economic development of countries like Japan, Singapore, the Republic of Korea, Thailand and Malaysia on which Chinese culture has had an extensive influence for a long period of time, is forcing specialists on Chinese issues the world over to reassess Chinese culture. We believe that Chinese culture and Western culture together constitute a complementary system which holds the key to rational solutions for global issues now and in the future.

SHEN CHENRU is a member of the Chinese Academy of Sciences. He is Editor-in-Chief of the Chinese language edition of the UNESCO periodical, *Impact of science on society* and of the dual language edition of *World Science and Technology*.

Having been for many years a department dean in a college of foreign languages, Professor Shen now devotes his time to science popularization.

ZHANG SHAOZONG is at the Institute of Geology of the Chinese Academy of Sciences and is currently the executive editor of the English language edition of *Scientia Geologica Sinica*.

Mr Zhang obtained a Masters degree from the Postgraduate School of the Chinese University of Science and Technology and maintains an interest in science, culture and society.

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JAPAN AND THE NICs

Sogo Okamura and Reg Henry

Science has played a key role in Japan's development since 1868 by transforming the productive base of its economy and influencing its society and culture. Having overcome many natural constraints to become one of the industrialized countries that lead the world in scientific research and technological innovation, Japan continues to believe that its future prosperity is heavily dependent on science and technology (S&T). Similarly, the role of S&T in the dramatic economic growth of the newly industrialized countries (NICs) of Asia since the 1960s cannot be overstated. Lacking the scientific tradition and the degree of industrialization that Japan possessed at the time, these countries launched a vigorous programme of S&T capability acquisition in order to support their burgeoning foreign-financed industries. This article briefly reviews the manner in which S&T has been utilized by Japan and the NICs to achieve industrial development and economic prosperity.

STATUS OF SCIENCE AND THE SCIENTIFIC ESTABLISHMENT IN JAPAN

Two factors were critical to Japan's rapid progress in science and technology: the government's role in promoting S&T, and the exceptional performance of the private sector in adopting, promoting and utilizing S&T.

The government's role in promoting, planning, administering and funding S&T has been significant and today it operates a vast network of agencies that formulate and implement Japan's science and technology policy. The network includes ministerial departments of government which plan and promote Japanese S&T in each productive sector; operational agencies such as the Science and Technology Agency (S&T) and the Ministry of Education, Science and Culture (MESC); and advisory bodies such as the Council for Science and Technology and the Science Council in MESC. In April 1992, the government adopted a resolution entitled General Guideline for Science and Technology Policy which recommended the development of a positive and comprehensive science and technology policy with the following three objectives in mind: 'the coexistence of human beings in harmony with the earth', 'the expansion of intellectual stock', and 'the construction of an attractive society where people can live with peace of mind'. In order to achieve these objectives, the General Guideline pointed out priority measures such as harmonizing S&T with man and society, promoting the development of human resources for S&T, increasing investment in R&D, upgrading R&D infrastructure, stimulating flexible and creative research, internationalizing Japan's S&T activities, and promoting S&T at the local level within Japan.

The government also funds and conducts research and development (R&D). Japan's General Guideline commits the government to supporting the R&D activities which are set out in Table 1.

TABLE 1
R&D AREAS TO BE SUPPORTED UNDER THE TERMS OF JAPAN'S GENERAL GUIDELINE

Basic and leading S&T
Materials science and technology
Information/electronics science and technology
Life science and biotechnology
Soft science and technology
Advanced basic science and technology
Space science and technology
Ocean science and technology
Earth science and technology

Science and technology for human coexistence
Preservation of the natural environment including the global environment
Development and utilization of energy sources
Development and recycling of resources
Continuous production of foods

Science and technology for enriching life and society
Maintenance and improvement of health
Improvement of the living environment
Improvement of the socio-economic foundation
Strengthening of disaster prevention and safety measures

Japan's investment in natural sciences R&D in 1991 was 2.76% of GNP, the highest proportion in the world, involving a total expenditure of ¥12.72 trillion (US$94.4 billion) which is only surpassed by the USA. In 1990, the

TABLE 2
JAPANESE GOVERNMENT SECTOR FUNDING AND EXECUTION OF R&D

	1980		1990	
	Total (¥ trillion)	Share of total (%)	Total (¥ trillion)	Share of total (%)
Expenditure on government executed R&D	1.09	23.4	1.78	14.7
Government R&D funding	1.21	25.8	1.99	16.5

government contributed 16.5% (¥1.99 trillion) of those R&D funds and conducted R&D worth ¥1.78 trillion (see Table 2).

Despite Japan's impressive total investment in natural sciences R&D, the government's contribution is only half that of governments in the major developed countries when measured as a percentage of GDP, and it is not growing in relation to private sector expenditure. On the contrary, it has been decreasing year by year. In fact, R&D expenditure in many Japanese companies now exceeds that of capital investment in plant and equipment. Nonetheless, the government sector's total R&D expenditure is significant because 32.8% of this amount goes to basic research compared with only 9.2% of non-government sector R&D funds. Furthermore, Japan's 1992 General Guideline outlines increased government funding for basic research. Finally, the government remains the major funding agency for university R&D although industry funding of university R&D is now 35%, up from 11.2% in 1980, and the universities' and government's proportion of total expenditure on basic research has declined from 64% in 1980 to 55% in 1990.

Private sector R&D expenditure has increased (Table 3) almost three-fold in most industrial sectors over the past decade, increasing its share to 80.6% of the national total in 1990, while universities contributed 11.6%, and government institutes 7.8%. This trend has skewed Japan's research infrastructure in that facilities and equipment in private industry are much better than in the other two sectors. Private sector R&D investment is also skewed because over 71.8% of all research expenditure is spent on development, 21.8% on applied research and only 6.4% on basic research. All this presents three problems for basic research in Japan. Firstly, the low proportion of private sector R&D expenditure on basic research, although amounting to 45% of the total basic research conducted in Japan, still leaves the government responsible for funding many areas. Secondly, private sector basic research is still differently motivated from that in government or university laboratories. Finally, the overall environment for basic research in Japan is still viewed as inferior to that in the USA and Europe, except in specific areas such as communications and electronics.

Science output is also uneven because companies are unwilling to allow publication of their basic research results. This lower output of academic publications contrasts strongly with Japanese patent applications which constituted 20% of the total in the USA and 15% in Europe in 1988.

Higher education in Japan is greatly affected by the high private sector demand for S&T and R&D personnel. Although there has been a continuous expansion in demand by all sectors, the increase of R&D personnel in the private sector has been the most striking. In the past 10 years, the share of the number of R&D personnel in private

TABLE 3
PRIVATE SECTOR R&D EXPENDITURE BY TYPE OF INDUSTRY IN JAPAN

	1981 (¥ trillion)	1990 (¥ trillion)
Electrical machinery	1.01	3.15
Transport equipment	0.63	1.50
Chemicals	0.62	1.42
General machinery	0.24	0.65
Precision instruments	0.12	0.34
Iron and steel	0.12	0.30
Ceramics	0.08	0.22
Other manufacturing	0.50	1.09
Non-manufacturing	0.26	0.61
Total	3.58	9.28

companies increased by 7%, whilst in research institutions and universities it decreased by 2% and 5% respectively (Table 4). An investigation by the Science Council in MESC shows that most research laboratories in private companies are planning to increase the number of R&D personnel in proportion to the increase of gross national product (GNP), but research institutions and universities will have serious difficulty in following suit unless the government offers significantly increased support.

Japan now employs 9.2 researchers per 1 000 employees, having overtaken the USA in this respect in 1986. As Japan, too, experiences the international trend of young people rejecting science and engineering careers, demand for scientists and engineers is outstripping supply.

In response to the General Guideline for Science and Technology Policy, and other reports of numerous councils and committees in various ministries and agencies claiming the importance of basic research, the government has been making efforts to expand R&D funding.

The second major factor in Japan's successful use of science and technology has been the performance of private sector enterprises in promoting and utilizing S&T. Japan's private sector adopted two approaches which were in some measure responsible for moulding national S&T development. The first was the emphasis placed by the private sector on market needs and product requirements in determining S&T strategy. This policy ultimately promoted S&T in Japan even though initially it undermined them. The second approach was to view the process of technological innovation as involving many creative factors, and not just the new technology itself. This sophisticated view of the innovation process benefited basic research because private enterprise diversified its R&D investment and sought more varied applications from it.

These two approaches to Japan's S&T by the private sector have produced other unusual R&D features. For example, R&D staff and engineers are very involved throughout the innovation process; R&D is conducted at each stage as industry sustains a close link between scientific research and production; companies are diversifying their product lines as 'technology complexes' rather than diversifying by merging capital; companies are being driven more by their new core technologies than by their original fields of business; complementarities between new technologies are drawing Japanese enterprises into technological interdependence and as a result a reduction in technological competition in the promotion of private R&D is becoming evident in Japan. In addition, a similar R&D interdependence has occurred at international level since 1985 after Japanese companies deployed R&D overseas and foreign firms increased their R&D investment in Japan, especially in the automobile and semiconductor industries.

TABLE 4
NUMBER OF PERSONS ENGAGED IN R&D IN THE NATURAL SCIENCES IN JAPAN

	1981		1991	
	Personnel	Share (%)	Personnel	Share (%)
Private companies	184 889	58.2	330 996	65.5
Research institutions	30 006	9.5	37 084	7.4
Universities	102 592	32.3	136 815	27.1
Total	317 487	100.0	504 895	100.0

All these government and private sector features and trends have shaped every aspect of science in Japan today. Recently the Japanese Government has been making efforts to establish research consortia such as the International Superconductor Technology Centre, the ERATO programme, the Institute for New Generation Technology, etc. These organizations are found to be very useful for strengthening university-government-industry cooperation as well as international collaboration.

TRENDS IN JAPAN

Two recent trends that have emerged as major factors in Japanese science are globalization and concern for the environment. These factors may necessitate rejecting Japan's competitive and nationalistic approach to science, while forcing an upgrading of government-conducted and sponsored basic research. The other major trend in science in Japan has been to respond to international environmental problems by using scientific research to identify causes of, and provide countermeasures for, global warming, acid rain and the destruction of the stratospheric ozone layer.

SCIENCE AND THE NIC MODEL

Despite its dramatic economic success since the Second World War, the early 1980s saw Japan being challenged as a model for developing countries by Asia's newly industrialized countries (NICs). Three republics in East Asia – the Republic of Korea, Singapore and Taiwan, and to a much lesser extent the Territory of Hong Kong, offered a model which had achieved rapid socio-economic success. A major feature of these NICs was their use of science to effect brisk economic growth. Today Asia's NIC model is a paradigm of the use of science to achieve development, and one which continues to offer hope to less successful developing countries.

Science became vital to the NICs after they explicitly adopted the central tenets of the post-war strategy for utilizing S&T for development. This strategy dictates that governments must introduce policies both to establish an indigenous S&T capacity, and to apply it to industrial production. Although such a policy has been adopted in most newly independent developing countries since the 1960s, the Asian NICs have been the most successful. Hong Kong is, however, an exception because it relied completely on private enterprise until 1980.

The reason for the NICs' success was their innovative implementation of the strategy. Most importantly, the NICs based their S&T policies on factors such as international market demand, foreign technology and foreign investment; that is, they did not blindly promote an indigenous S&T capability in the belief that it would automatically contribute to economic growth. Further, the NICs closely integrated S&T promotion with pragmatic policies to correct national problems such as trade deficits, debts, or unemployment. For instance, the Republic of Korea responded to comparative disadvantages in manufacturing in 1980 by requiring private industry to establish R&D facilities or to form R&D consortia. Similarly, Singapore modified its policy of relying on foreign corporations for industrial technology after international circumstances changed in the late 1970s, and began to promote local R&D as well. That pragmatic integration of S&T policy making with development policy remains the major feature of the NICs.

SCIENCE AND PLANNED DEVELOPMENT

Initially, such S&T policy innovation, pragmatism and integration resulted from NIC government policies and actions. The sophisticated developmental agencies which managed NIC economies readily provided those skills because they always accepted S&T as essential ingredients for their capitalist development models. Agencies that command-planned NIC economies, bureaucratically controlled their societies or operated state-owned industrial enterprises and statutory boards, such as the Republic of Korea's Economic Planning Board (EPB), Taiwan's Council of Economic Planning and Development (CEPD) or Singapore's Economic Development Board (EDB), which simultaneously promoted science and stimulated the acquisition of technology.

NIC governments also established specific institutions to promote, manage and fund S&T. These included the Republic of Korea's Ministry of Science and Technology (MOST) and National Council for Science and Technology (NCST), Taiwan's National Science Council (NSC) and Singapore's National Science and Technology Board (NSTB) or Science Council. These bodies successfully established an indigenous S&T capacity by promoting university research and education, by creating national R&D institutes such as the Republic of Korea's Advanced Institute of Science and Technology (KAIST) or Taiwan's NSC research laboratories, and by building a modern science infrastructure. NIC governments also encouraged local R&D by planning and promoting science, by providing trade protection and subsidies, by offering special tax concessions and R&D allowances, by upgrading education and planning human resources development, by encouraging foreign capital and technology, and by enacting special legislation.

These policies, which were aimed at co-opting the private sector to promote S&T, achieved notable success. The resulting private sector promotion of science involved two distinct facets. The first was to undertake industrial R&D. The second was to improve their scientific skills to facilitate the use of S&T from abroad. NIC governments were singularly successful in stimulating private sector action on both those S&T fronts. Their success was due to their astute management of the entire developmental context, and to their flexible administration of S&T promotional policies to meet private sector needs. This was most evident when NIC private sectors gained access to foreign technology as a result of one-stop investment administration provided by government agencies such as the Republic of Korea's Foreign Capital Inducement Deliberation Committee (FCIDC) or Taiwan's Industrial Development and Investment Center (IDIC). It was also evident when innovative collaborative arrangements such as Export Processing Zones (EPZs) and Free Trade Zones (FTZs) attracted new technology for NIC manufacturers.

Over time, the three NIC republics have integrated both governmental and non-governmental components of their S&T policy. The government's S&T infrastructure and private sector S&T-based industries became linked as the upgraded S&T infrastructure allowed NIC private sector industries to change the terms under which they acquired foreign technology, and to gain greater partnership in technology sharing and improved technological diffusion. This enhanced private sector S&T capacity made government policies to acquire higher value-added industries more feasible. The NICs' endogenous S&T capacity now allows them to innovate, and Taiwan and Singapore are currently initiating the 'discovery push' process achieved already by the Republic of Korea's electronics and microchip technologies.

In retrospect, science has been successfully entrenched in the NICs as a result of several factors. Most fundamentally, government policies for development successfully linked NIC industries to First World economies, controlled foreign investment and facilitated collaboration with transnational corporations. This created a context in which NIC private sectors could harness imported technologies for industrial development. Assisted by governmental policies and well-managed agencies, private sector enterprises were also able to vertically integrate and deepen the technological capability of their local industry to become, eventually, S&T innovators drawing on their endogenous capacity.

This is where NIC and non-NIC implementation of the S&T for development strategy diverge sharply. So far, non-NIC developing countries have not integrated local S&T promotion with the management of imported S&T to create the endogenous S&T capacity that might allow them to emulate the late industrialization of the NICs. As a result they remain unprepared for future science-based development. Meanwhile the Republic of Korea, which was the first of the Asian NICs to recognize explicitly the importance of endogenous S&T, has narrowed the gap with Japan, Singapore is explicitly promoting endogenous S&T, as is Taiwan under its Ten Year S&T Development Plan (1986-95), and even Hong Kong is remedying its endogenous S&T weaknesses.

CURRENT SCIENCE TRENDS

The current concern of NIC policies is to sustain their developmental success. For this reason, S&T promotion is a significant feature of NIC education, research and

TABLE 5
R&D EXPENDITURE OF THE NICs EXPRESSED IN REAL TERMS AND AS A PROPORTION OF GNP

	1981		1985		1990	
	Value	% GNP	Value	% GNP	Value	% GNP
Korea, Rep. of (US$ million)	418	0.64	1 298.0	1.48	4 481	1.91
Taiwan (NT$ million)	16 414	0.93	28 702.0	0.98	71 500	1.65
Singapore (S$ million)	81	0.3	241.3	0.6	572	1.10

industrial development. This is indicated by the high national R&D expenditure in the three NIC republics, and by its continuing growth both in absolute terms and as a proportion of their expanding GNP (Table 5).

Government investment in R&D varies greatly among the Asian NICs at the moment. Much higher government proportions of R&D investment by Taiwan and Singapore are evident in comparison with the Republic of Korea, where it has decreased to 16%, the level of investment seen in Japan (Table 6). Recently, however, the proportion of government investment in Taiwan and Singapore has also been declining as that of the private sector rapidly increases.

TABLE 6
GOVERNMENT EXPENDITURE ON R&D IN THE NICs AS A PERCENTAGE OF TOTAL

	1981 (%)	1985 (%)	1990 (%)
Korea, Rep. of	44	19	16
Taiwan	53	60	46
Singapore	45	50	46

History explains the higher government R&D investment proportions in Taiwan and Singapore where, during the mid-1980s, policies were adopted to expand government S&T activity instead of relying on private sector enterprises. For instance, Taiwan's first Science and Technology Development Programme in 1979 designated eight major S&T projects to accelerate economic development, increase public welfare, consolidate national defence and promote modernization. Singapore in 1980 began its new strategy of providing government support for R&D in its research organizations, universities and industries, as well as encouraging SMEs (small and medium enterprises) to seek higher value-added production through R&D.

The Korean experience suggests that government expenditure on R&D in Taiwan and Singapore will continue to decline in the future. R&D in all four NICs is now dependent upon and dominated by the private sector irrespective of whether S&T were state-promoted or dependent on free-enterprise in the past. This situation has narrowed the historical differences between Taiwan and the Republic of Korea on the one hand, and Singapore and Hong Kong on the other.

This dominant private sector trend is the result of government policies and factors which successfully promoted R&D by large, medium and small enterprises, used science parks to attract foreign S&T, and promoted local R&D. It also results from continuing government subsidies for R&D. For instance, Taiwan subsidizes key components and product development, and collaborates in promoting the five top-priority industries of consumer electronics, computers, communications, automation and advanced materials. The trend has been assisted by NIC governments softening their regulatory approach towards foreign investors, relaxing rules on foreign equity, facilitating the import of technology, and especially by changing their administrative style. Planning objectives are now achieved by inducement rather than direct control, research goals are achieved under collaborative arrangements with the private sector which is encouraged to increase R&D expenditure in order to 'breed' high technology winners. Meanwhile, the government itself plays only a supervisory and facilitatory role to improve value-added manufacturing.

This new government role is evident in recent special basic research programmes and the awarding of research grants in the NIC republics, many of which promote high technology collaboration. In 1992, Taiwan announced in its Mid-Term Six Year Plan (1991-96), R&D projects that aim to accelerate all aspects of S&T in cooperation with the private sector. Singapore's NSTB funded 12 joint public and private sector R&D projects worth S$11 million in 1991, double the amount of the previous year, and a collaborative Magnetic Technology Centre was opened in 1992 to strengthen R&D on new materials. Such collaborative activities take place in S&T parks in Singapore, Taiwan and the Republic of Korea, supported by government agencies. These measures have resulted in the Asian NIC republics leading other developing countries in research cooperation between government, university and the private sector.

Thus NIC governments still bear a major responsibility in funding and conducting R&D, especially in the initial stages of high technology promotion and in the basic sciences. Singapore for example now funds eight research institutes, as well as R&D in public sector departments. The governments also bear major managerial responsibilities. This role derives partly from the inertia of the older institutions in promoting S&T for development and partly from the state-owned enterprises in the Republic of Korea, Taiwan and Singapore that originally initiated demands for S&T education, R&D facilities or trained R&D manpower, and which now create forward linkages for new S&T in collaboration with the private sector. The Republic of Korea's early success with such collaboration has been emulated by the other two republics; Singapore has created public sector corporations and research institutes which have been used since 1988 to promote R&D automation and biotechnology and, in 1991, to train private sector researchers under an exchange scheme.

The output from scientific research in the NICs has been unbalanced because of the initial use of science for applied developmental purposes. For instance, there is a major disparity between the number of patents and research publications in the NICs. On the one hand, the emphasis on applied research in the NICs is still evident from the growth in granted patents. The Republic of Korea granted 1 808 patents in 1981 and 3 972 in 1989 while Taiwan granted 6 265 in 1981 and 10 123 in 1991, and Hong Kong has granted approximately 1 000 patents each year since 1985, though largely to foreigners. Although foreigners dominate the generation of new inventions in Taiwan, new designs and utility models are now predominantly created by locals. The NICs' success in the application of S&T is also evident from the USA patents granted to Taiwanese and Korean nationals, amounting to 807 and 236, with a ranking of 11th and 16th respectively in 1990. On the other hand, the *Science Citation Index* places the NICs well behind other developing nations in their ranking for published S&T papers (Table 7).

However, this historical imbalance is changing. For instance, Taiwan's S&T research publications raised its ranking from 37th to 28th between 1985 and 1990. Taiwan has also achieved prominence in engineering research and was ranked 13th nation in the world in 1990

TABLE 7
SCIENTIFIC AND TECHNICAL RESEARCH PAPERS PRODUCED BY THE NICs

	1988	1989	1990	World ranking 1990
Taiwan	2 001	2 302	2 861	28
Korea, Rep. of	1 227	1 567	1 780	33
Hong Kong	904	1 081	1 150	40
Singapore	653	739	843	44

as well as being third in research, after the USA and Japan, in the electronic, information and telecommunication engineering areas.

The growth in R&D personnel in the NICs has been very rapid. Singapore has progressed from eight to 27 researchers per 10 000 in the labour force between 1978 and 1988 and attained 32 per 10 000 in 1991. The Republic of Korea has increased from one to 16.4 researchers per 10 000 employees over the 25 years from 1965, but remains behind Taiwan's 22.6 per 10 000 in 1990. Recent figures suggest that this expansion in research personnel is accelerating (Table 8).

TABLE 8
NUMBER OF RESEARCHERS (SCIENTISTS AND ENGINEERS) IN THE NICs

	1981	1990	1991
Korea, Rep. of	20 718	70 503	not available
Taiwan	19 604	46 060	not available
Singapore	2 741	4 329	5 019

The growing demand for research personnel has resulted in dramatic increases in higher education enrolment, especially in graduate schools. In the Republic of Korea, the increase has been ten-fold since 1970. This increase has been accompanied by a rapid enhancement in R&D expenditure by higher educational institutions. In Singapore, R&D expenditure by its two universities increased in real terms from S$24.3 million in 1981 to S$180.42 million in 1992, even though their share of national R&D declined over the same period. Hong Kong has expanded as well, and seven third-level institutions now exist with their research supported by the Government University and Polytechnic Grants Committee. Hong Kong's newest university, the Hong Kong University of Science and Technology, has been expressly created to promote research in science, technology and engineering because the Territory possesses no national or major corporate R&D laboratories, yet seeks to become a high-technology-based economy.

REGIONAL TRENDS

Thus, the Asian NIC model is significant today with regard to all aspects of science, partly because of the pre-eminence it gave to S&T in development, partly because it highlights the importance of flexible government policies and management, but mostly because it has confirmed to all developing countries that S&T are crucial for their future.

The NICs continue to promote their endogenous S&T capacity while acquiring new technologies from abroad for industrial development. NIC government co-option of the private sector for the promotion of S&T has progressed through all the various regulatory phases to the current 'small government' stage. Now, their endogenous S&T allow the NICs to take a technological leap into the future by adapting their R&D to new national goals, as the Republic of Korea did when it shifted its electronics industry from micro-chip manufacture to value-added products. Furthermore, this endogenous S&T capacity is being directed to meet new R&D priorities as environmental questions emerge in the NICs.

Nevertheless the NICs face certain problems in relation to science. They intend raising their general S&T levels because they still remain below those of the USA and Europe, especially in technological innovation. Even the Republic of Korea and Taiwan, the most successful Asian NICs, face problems; measures of their technological capability suggest that, despite rapid improvement, they remain well below the levels of the USA and Japan (6.0 and 9.2 on a 1987 index with USA 100 and Japan 99.5). Also, despite the Republic of Korea's and Taiwan's success in increasing their export of technology-intensive products, their payments for technology have increased at a faster rate resulting in a negative technological balance of payments that will test the future success of science in the NICs.

SOGO OKAMURA is the President of Tokyo Denki University. He also serves as Senior Adviser to the Rector of the United Nations University and is Professor Emeritus of the University of Tokyo.

In addition to his academic responsibilities, Professor Okamura has served as Vice-Chairman of the OECD's Committee for Scientific and Technological Policy, Chairman of the Science Division of the Japanese National Commission for UNESCO, Chairman of the Engineering Division of the Science Council of Japan, Chairman of the Japanese Radio Regulatory Council and Director-General of the Japan Society for the Promotion of Science. Professor Okamura holds office in several professional associations and has also received numerous national awards for his services.

REG HENRY is Senior Lecturer in Environmental and Science Policy at Griffith University, Brisbane, Australia. Trained in Law and Political Science at Melbourne and La Trobe Universities, Mr Henry served as Senior Teaching Fellow both in India and at La Trobe University before joining Griffith in January 1977. He has served as consultant to UNESCO on a number of occasions, notably in connection with the regional ministerial conference on science and technology, CASTASIA II.

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AUSTRALIA AND EAST ASIA

Reg Henry

The advancement of science and technology (S&T) in the East Asian region was stimulated by the S&T-based developmental success of Japan and is now benefiting further from the more recent success of the four newly industrialized countries (NICs) of Asia. These countries – the Republic of Korea, Taiwan, Singapore and Hong Kong – have demonstrated the value of S&T in economic development by increasing productivity and growth through skilled science management. Neighbouring non-NIC countries like Indonesia, Thailand, Malaysia and the Philippines have attempted to emulate the economic success of the NICs by imitating their science management techniques. And they are very likely to achieve industrial sector growth similar to the NICs because they already possess very similar science institutions and infrastructure as well as some comparable S&T capacities.

TABLE 1
AUSTRALIAN FEDERAL SUPPORT FOR MAJOR PROGRAMMES OF SCIENCE AND INNOVATION

	1990-91 Australian $ (millions)	1991-92 Australian $ (millions)	Real change
CSIRO	421.1	448.2	+3%
DSTO	227.2	221.1	–6%
Other R&D agencies	211.6	222.4	+0%
Australian Research Council	172.4	241.8	+37%
Other higher education R&D	815.0	840.0	–6%
Cooperative research centres	–	19.5	na
Industry R&D and incentives	360.4	361.7	–3%
Rural R&D	82.2	104.7	+23%
NH and MRC	94.7	103.3	+6%
Other health R&D	11.6	18.7	+56%
Other R&D grants	26.2	26.0	–4%
Total	2 422.0	2 607.0	+4.3%

na: not available.

Source: *Science and Technology Budget Statement 1991-92*, Australian Government Publishing Service, Canberra 1991.

The recent trend towards imitating NIC science management is logical in the countries of a region where science was derived from the same sources, comparable organizations were established to promote science and similar features and problems were manifested. For instance, analogous government scientific services and universities created during the colonial era were, after independence, similarly expanded and reshaped to meet common S&T for development needs. This resulted in a regional pattern in which government ministries coordinate science policy, conduct and fund research in universities and agencies, promote and guide private sector research, and support and supervise all aspects of the S&T infrastructure. The problems encountered by these organizational systems have driven some East Asian countries to replicate NIC institutions for acquiring, adapting and creating new S&T or encouraging private sector research and development (R&D). The result has been a regional trend towards establishing, as in Japan, a strong private sector science capacity with characteristic government guidance.

While it is logical that developing countries should imitate the NICs, it is surprising that science in the developed countries of the region like Australia and New Zealand should be influenced by them. In Australia, policies to replicate NIC success are modifying well-established scientific institutions and changing the role of science. This is partly because Australian science also reflects the region's organizational pattern of governments being responsible for, and central to, all aspects of S&T policy. Although the Australian Government is advised by expert bodies, such as the Australian Science and Technology Council and the Academies or sectoral Councils, it still controls science policy. It also dominates research because it carries out 60% of R&D in official agencies such as the Commonwealth Scientific and Industrial Research Organization (CSIRO), the Australian Nuclear Science and Technology Organization, the Australian Institute of Marine Sciences and the Defence Science and Technology Organization (DSTO), and in universities.

The influence of the NICs was seen when research policy was redirected to favour the applied sciences in the industrial and manufacturing sectors. Comparisons with the NICs also cause Australia's R&D to be seen as inadequate for sustaining economic development or increasing international competitiveness; Australia's private industrial R&D level is still considered too low, despite increasing rapidly from 20% to 40% of national R&D in a decade, spurred by unflattering comparisons with Korea and Japan. Furthermore, official reviews of science in Australia have recommended organizational changes specifically based on NIC experience. Most notable were those in 1987 to improve links with productive sectors by both reconstituting the CSIRO's many research divisions and 7 000 staff into six major institutes and by creating a Department of Industry, Technology and Commerce (DITAC) in place of a Science and Technology ministry and to promote skills related to economic needs by restructuring third-level education and by integrating university S&T research with industry.

Despite differences between Australia and the East Asian countries such as the percentage of gross domestic product (GDP) spent on R&D (1.3% compared with 0.2% or 0.3%), the significant feature of regional science now is the strength of its institutionalization. It is this institutionalization that makes NIC achievements from science appear very attainable by other countries and accounts for regional government trends to promote private and public sector research cooperation, refine policy instruments, reform infrastructure, and coordinate processes to maximize competitive advantage. Their common goal is to achieve growth from high-technology promotion, meet market demands and attract investment. Whatever the outcome of such organizational and policy changes to replicate NIC achievements, they ensure that science remains central to the future of the region.

TABLE 2
GROWTH IN R&D LEVELS AND EXTERNAL PATENTING OVER THE 1980s – COMPARISONS BETWEEN AUSTRALIA AND OECD NATIONS

	Average for 19 OECD countries			*Australia*		
	1981 or nearest year (per unit GDP)	1989 or nearest year (per unit GDP)	Average annual real growth (%)	1981 or nearest year (per unit GDP)	1989 or nearest year (per unit GDP)	Average annual real growth (%)
Gross expenditure on R&D	1.55	1.87	+5.7%	1.00	1.23	+6.7%
Government funding of R&D	0.71	0.74	+3.3%	0.73	0.67	+2.2%
Business funding of R&D	0.78	1.05	+8.0%	0.24	0.52	+15.2%
R&D expenditure in government agencies and universities	0.61	0.65	+3.7%	0.75	0.72	+2.4%
R&D expenditure in business enterprises	0.91	1.18	+7.4%	0.25	0.51	+14.0%
External patent applications by residents[1]	5.8	8.8	+9.2%	2.7	6.1	+17.5%

1. Since the numerator in the ratio is no longer in units of national currency, the GDP values used are expressed in $US million at constant 1985 prices.

Source: *Science and Technology Budget Statement 1991-92*, Australian Government Publishing Service, Canberra 1991.

2 SCIENCE AND TECHNOLOGY SYSTEMS

INSTITUTIONS

Pierre Papon and Rémi Barré

Scientific research and the development of technology are areas of human endeavour which no one society has monopolized. China and the Islamic countries managed to give a relatively organized and developed form to scientific activity long before any European state, and the credit for major discoveries in the fields of magnetism, acoustics and optics is rightly theirs. The leading role played by science and technology (S&T) in our societies today is the result of a lengthy evolutionary process which has gradually given rise to the emergence of 'modern science' and the technical know-how on which technology is based: the sciences and their application are the result of history.

Each civilization has given its stamp to a form of social organization which enabled scientific and technological activity to be pursued in more or less close symbiosis with the society in question. Thus it was that, very early on, almost every large city in the Islamic world had an astronomical observatory. Those of Baghdad, Cairo and Samarkand played a major role in the development of astronomy from the 9th century onwards. Similarly, in China, the Imperial State set up a public service with multiple functions in which science and technology were of significant importance. Astronomy was to a certain extent considered to be an official science since, in agrarian countries, astronomers were employed in the manufacture of calendars; the same was true of mathematics, physics and above all hydraulics. Most societies have therefore sought at a very early stage to stabilize the production of scientific and technological knowledge, a process that today we would call technological research and development.

It was in Western Europe during the Renaissance, however, that science acquired a stable institutional form in which it was able to declare its independence from philosophy and theology. For many centuries afterwards, this work of learned men (it had yet to be called 'scientific research') was restricted to academies or the teaching chairs of universities and colleges. The first modern scientific institution was in all probability the *Accademia dei Lincei,* founded in Rome in 1609 and to which Galileo belonged. The scientific academies of London and Paris (respectively founded in 1660 and 1666) were real institutional innovations: their purpose was to replace purely philosophical speculation with observation and experiment. They also created a new relationship between science and political power, since they made 'scientific research' official business.

Since that time, the logic of scientific discovery has become institutionalized little by little. The context gradually changed during the 19th century, for scientists, far-seeing administrators of universities and a certain number of clear-headed politicians became aware of the fact that in Europe the production of scientific knowledge could no longer be the affair of isolated, albeit brilliant individuals. Scientific research required major resources: laboratories and complex equipment, professors with assistants, students, research teams and technicians. Research institutes were therefore created within universities, and later as independent establishments. Germany was the first to understand the need to create a new research organization to meet the objectives in hand. The establishment in 1911 of the Kaiser Wilhelm Research Society (today the Max Planck Society) was the real turning point: for the first time a state had created a research institute outside the university system.

At the same time, industry was also setting up its own research laboratories, and the scientific discoveries they made possible were the source of first-rate technological innovation, especially in chemistry.

Today, science and technology are basic components of human activity in modern society. Providing backing for scientific research to generate new understanding, stimulating technological innovation and launching wide-scale scientific or technological programmes are nowadays all integral parts of public policy, along with their industrial and military counterparts and corporate strategy. Setting up research programmes, utilizing results obtained by publicly financed laboratories, stimulating innovation in and strategy for industrial research, meeting social requirements, organizing international cooperation programmes and training specialists all require a wealth of protagonists, institutions and decision-making procedures. Altogether these form a genuine S&T 'system' having both national and international components. National research and technology policies, and those of industrial groups, are designed to keep this system not only alive but evolving, within public and private institutions, to update the objectives and make the choices and decisions necessary as part of the strategy behind our collective aims and ambitions.

THE MAIN PURPOSES OF RESEARCH AND TECHNOLOGY

Scientific research, like most of the work involved in technological development, today means mobilizing the skills of a wide range of professionals, from university scholars and scientists to engineers and technicians. The purpose of their work and therefore the functions occupied by the professionals involved are, of course, highly varied. Broadly speaking, they can be broken down into five main categories, as follows.

Production of basic S&T knowledge

This is the main purpose of basic or fundamental research, the results of which are published in articles in scientific journals (if every discipline is included, more than 75 000 titles of specialized periodicals have been recorded), or disseminated at meetings and conferences. This type of activity also provides the input to databases.

Training

In most university systems, teachers are also involved in research work. This provides some guarantee of quality in higher education, as well as being instructive for the students, in particular for those doing postgraduate work. It should be emphasized that in many countries today, this training is also carried out by scientists and research engineers from both public and private laboratories.

Production of knowledge and technical expertise required for public policy

A great deal of government work consists of defining technical standards and regulations by means of various types of procedures that could be described as 'the daily practice of scientific expertise and technological evaluation'. This includes control commissions for new chemical and pharmaceutical products, the evaluation of industrial and technological risks, the monitoring of water quality, etc. All this work is based on the expertise of scientists who for the most part work for public establishments. The environment, public health and the food industry are all examples of sectors where technical expertise is playing an increasingly important role in our society, involving appraisal, diagnostics, situation analysis reports and technical questions of all sorts (such as the state of the environment, the safety of an industrial facility, and so on).

Contribution to national strategic programmes

Modern states very often have 'strategic' objectives, in the broad sense of the word, as part of their power logic: they require complex weapons systems that do not depend on foreign nations' know-how, need satellites to ensure control over their own telecommunications, and wish to be energy-independent. To meet these objectives they have to set up large-scale technological research and development (R&D) programmes within their main public research organizations covering areas such as nuclear or aerospace research. These programmes are also implemented, in industrialized countries at least, in the laboratories of industrial corporations (in the public or private sectors) in fields such as electronics or aeronautics. The results of this work generally remain unpublished, and form the basis of international competition which does not follow free-market principles.

Participation in industrial innovation

The so-called R&D phase takes place upstream of innovation, that is, before the first use or commercialization of goods or services. Scientists and research engineers, particularly in industrial corporations, are therefore involved in a process which results in the development of new products and processes which are to be industrialized and marketed. Research work, generally applied in nature, often obeys economic rules based on stimulating corporate innovation. It should be noted, however, that not every innovation is the result of research work. Design and engineering offices, manufacturing departments, heavy industry and the service industries are also sources of innovation (software systems are increasingly innovations in themselves, for example).

One might say, by analogy with scientific research, that the patent is the basic product of technological activity. It is an intangible asset, like a scientific publication, but it gives its holder a monopoly and has market value, which a scientific publication does not. The patent recognizes an invention, such as an industrial process, or a new product or material. All fields of technology included, 85 000 patents were granted in the USA in 1990 to inventors of every nationality, and 55 000 in Europe (patents directly registered through European channels).

Technological innovation is also integrated into the capital goods and components of various types that a company develops or uses for production purposes. For example a car industry assembly line may use various computers to control the robots involved in the manufacturing process. Innovation is therefore the product of highly diverse processes.

All these S&T activities, some of which, as we have seen, date from many centuries ago, were embodied within a concept which gradually emerged at the start of the 1960s, that of R&D. Work by the Organization for Economic Cooperation and Development (OECD) on the statistics of research expenditure has played a major role in the agreement by experts upon a common typology that, over the last 30 years, has come to be known as the *Frascati Manual*. The manual defines three categories of R&D work.

Basic or fundamental research covers all the experimental and theoretical work undertaken to acquire basic knowledge on observable phenomena and events, without the scientists having any *a priori* prospective applications for their work. Major names in science such as Albert Einstein, Max Planck, Vantaka Raman, Jacques Monod and many others worked and continue to work with this state of mind, and they may be appropriately deemed 'fundamentalists'. Applied research, on the other hand, corresponds to innovative work whose purpose is to acquire new knowledge for practical application (industrial, for example). The work by Louis Pasteur in the 19th century on fermentation or silkworm disease was applied research, even though some of the discoveries he made in the process were 'fundamental' in nature. There remains a third category of research work: experimental development. This involves systematic work based on existing knowledge obtained via research work or practical experimentation, in order to manufacture new products or develop new industrial processes. For example, the discovery of new polymers by research laboratories gave rise to the manufacture of plastics, but transfer to the industrial phase was only possible after investment in further development work, requiring the setting up of pilot plants for testing and refining.

We can thus see how basic research, applied research and development are linked within our typology of S&T (our five categories). While the border between basic and applied research is often hazy, it is clear nonetheless that in almost all national S&T systems, it is basically the commercial companies and certain state technological organizations (civilian and military nuclear power stations, or petroleum research institutes, for instance) that carry out development work, linked either to the target of stimulating industrial innovation, or to strategic state programmes. Basic research is very often linked to training, while applied research is to be found as often in institutions producing the knowledge and technical expertise required for public policy, as in those involved in the development of strategic state programmes, and of course in industrial research laboratories.

As with any other form of classification, the *Frascati Manual* lends itself to criticism. Why, one might ask, do we need a taxonomy of S&T activities on which everyone agrees? Classification, however, is not just the obsession of statisticians or research and technology administrators. Its motivation lies in the desire of political and administrative authorities and captains of industry in every country around the world to have solid grounds for strategic decisions.

Furthermore, while the notion of development is more or less clear when referring to industrial activities, it is worth observing that it is much hazier when applied to military matters (such as the development of new weapons). The defence ministries of the main industrial countries (the USA, the UK, Russia, etc.) classify under this heading prototype test work (of military aeroplanes for example) which, in general, is extremely expensive. One has to be prudent, therefore, when analysing national R&D strategies, since for some countries this entails accounting for the fact that the concept of development has been expanded to cover certain work for military purposes.

Similarly, the dichotomy between basic and applied research is not always relevant, either from the scientific point of view or from that of economics. Is research on the role of carbon dioxide and other chemical substances in the 'greenhouse effect' basic or applied? The distinction is sometimes specious, it has to be said. In certain industrialized or developing countries where the public research sector is very large, we are led to distinguish between public R&D expenditure allocated to basic (or fundamental) research on the one hand, and that allotted to research programmes of collective interest on the other. In areas such as public health, the environment, energy, telecommunications and transport, public research organizations perform basic and applied research which is directly linked to public assignments in the broad sense of the term, such as enhancing the health of our fellow citizens, understanding environmental evolution, and so on. Since a great deal of their work is therefore 'finalized', we may consider their research to be equally finalized, and aiming to meet a social requirement. In Anglo-Saxon R&D terminology, this type of research is referred to as being 'mission-oriented'. It is, in a way, finalized research work on the borderline between basic and applied research. In this category we may classify a large part of the work in the biomedical sciences (for example that on the HIV virus or on tropical diseases), in the areas of the environment, energy control, the engineering sciences, and basic technological research in data processing and robotics, etc. Such work is carried out in research institutes, councils and agencies in the public sector.

PROTAGONISTS IN THE NATIONAL S&T SYSTEM

Public institutions, company laboratories, scientists, research engineers, technicians and administrative staff are all protagonists making up their national S&T systems. While each country has fashioned its national R&D system as a function of its own history, culture and customs, it is nonetheless possible, over and above the institutional forms necessarily specific to each country, to describe a technological R&D system in general, highlighting the main types of protagonists as defined by their roles and their functions within the system.

Universities

It was the universities that founded the first research laboratories, at least in Europe (although astronomical observatories were set up very early on, as we have mentioned, in Islamic countries and in China). Research laboratories in higher education establishments ('classical' universities, polytechnic institutes and independent schools of engineering) have two different roles: they teach and train scientists and engineers on the one hand, and carry out research to generate new S&T knowledge on the other. In terms of tradition and vocation, a university is where the training takes place of scientific personnel needing the basic knowledge, techniques, methods and networks of professional contacts required both for academic and industrial research. The system emphasizes the acquisition of knowledge and the preparation and defence of a postgraduate thesis by the young scientist. A university is also one of the places where basic research is carried out, i.e. where fundamental scientific knowledge is produced, aiming, in an increasingly large number of fields, at the construction of predictive models, some of which can have major impacts on technological innovation with the emergence of new paradigms. This is true, for example, today, of the interface between molecular biology and biotechnology; it was also the case in the application of quantum physics to the study of the states of matter.

The over-riding characteristic of the university type of research is that it is governed by the rule of publishing the knowledge obtained, which therefore has the status of public property.

Universities take up between 10% and 20% of the total outlay for research in developed industrialized countries. The percentage is higher in a large number of developing countries where the academic system provides the framework for the national research system. University research is mainly financed by annual budgetary allocations at national and, increasingly, at regional levels. In the industrialized countries, a growing part of the university research budget comes from industrial contracts and public finance for projects and programmes allocated by research organizations or agencies.

Public research organizations

These are institutions which carry out R&D work for the state, as part of the various responsibilities of the public authorities over and above training. Therefore, research in these organizations has well determined objectives, corresponding to explicit projects. Their legal status as well as what they are called varies considerably from one country to the next and even within each country. In English-speaking countries, they tend to be classified under the heading 'government laboratories' or 'administrative research'. In other countries they are called 'institutes', 'centres' and even 'academies'. Three types of institution can be distinguished according to their objectives:

- Institutions of a 'general' orientation, whose task is to support basic research in all the disciplines on programme by creating laboratories or institutes with their own staff. The *Centre national de la recherche scientifique* (CNRS) in France, the *Max-Planck-Gesellschaft* (MPG) in Germany, the *Consiglio Nazionale delle Ricerche* (CNR) in Italy, and their equivalents in countries in Latin America (e.g. the *Conselho Nacional des Desenvolvimento Cientifico e Tecnologico* (CNPq) in Brazil) and Asia, are the prototypes of institutions often created, in Europe at least, to make up for shortcomings in university research. The Science Academies of Russia, Poland, Hungary and China also fall into this category. It is worth noting that the links between these Academies and university research are highly tenuous, even non-existent in certain cases, while other research organizations, such as the French CNRS, have close links with university research.
- Institutions carrying out the research required for the exercise of management and legislative responsibilities by the state in the areas with which it is concerned, such as public health or the environment, but also for the management of state forests or maritime zones. The corresponding public research organizations have, among other things, a role as technical experts in relation to the public authorities, particularly in the drafting of legislation; in general they tend to develop, in their specific field, 'mission-oriented' research and provide back-up for the professional sectors with which they have ties. In many developed or developing countries a great number of public research organizations with this type of brief have been set up over the last few decades, such as national institutes or councils for medical, agricultural, marine or environmental research.
- Organizations conducting research required for the exercise of the responsibilities of the state in terms of large-scale facilities and S&T infrastructures. This is the area of strategic state objectives which result in the engineering of complex technological systems. Included in this category are fields like the aerospace industry, nuclear energy, telecommunications and advanced weapons systems, as well as large-scale scientific devices and systems such as particle accelerators, nuclear fusion facilities, scientific satellites and oceanographic vessels. More often than not these are long-term projects whose annual costs can run into hundreds of millions of dollars (even billions of dollars in the case of planned particle accelerators). The projects often go hand in hand with the development of the related industrial sector, such as the electronics or aerospace industries. The development programmes take place in civilian or military centres, such as national centres or commissions for atomic energy, aerospace research or telecommunications.

The number and size of these public research organizations vary greatly from country to country, given the differences in attitude towards the responsibilities of the public authorities and the differing levels of military expenditure. Another factor which varies greatly from one country to the next is the percentage of research performed directly by public organizations and that which is sub-contracted to industrial enterprise.

Public research-funding institutions

This type of player on the technological R&D stage differs from the two mentioned above in that it does not carry out the research work itself, but finances research performed on a contractual basis by industry, university or public research organizations. The research is financed from a specific budget allocation by the agency in question as part of its brief from the public authorities, a brief which theoretically implies the carrying out of research. The agencies' task is therefore similar to that of a public research organization, except for the fact that, since they have no laboratories, they sub-contract all the research. It should be emphasized, however, that they do play a vital role as programme designers, coordinators and managers. In most cases the status of the agencies is that of a public establishment, which gives them considerable leeway. Their projects can involve basic, applied or finalized research, but very rarely development (although aerospace is a noteworthy exception). Thus we find in this category the National Science Foundation (NSF) in the USA, the *Deutsche Forschungsgemeinschaft* (DFG) in Germany, the *Fonds national pour la recherche scientifique* in Switzerland, the National Science Foundation in China, space agencies such the *Centre national pour les études spatiales* (CNES) in France, and agencies for environmental studies, energy conservation, scientific cooperation policy support, etc.

Industrial research laboratories

Sometimes considered to be the key factor in developed industrial economies, the industrial research laboratory is the place where technological innovation is carried out by scientists and research engineers trained in the universities and polytechnic institutes. The key to the efficiency of industrial research lies in its harmony with an industrial corporate strategy, the quality of its interaction with the marketing and production departments, and its capacity to bring about further investment for development, design, marketing, production and distribution. Technology implemented by a firm for innovative purposes is not exclusively provided by its research laboratory but also, sometimes exclusively, from a wide range of other sources. These may include the know-how of specially recruited scientists and engineers, scientific and professional meetings and, more generally, the exchange of information with customers, suppliers and competitors, as well as the monitoring of products launched by competing organizations.

All these vectors of technological and scientific information are powerful means for non-stop circulation of technology from the local to the global level. Yet this does not mean that technology is ownerless or public property: in every case the very nature of the technology – its partially tacit and company-specific character – implies that its efficient integration into the products and processes of the receiving (or copying) company takes time and costs money. As a result, industrial R&D is often considered to be the optimum means of integrating and disseminating technological and applied scientific know-how. Companies are led both to protect their discoveries and innovations by patenting them, and to take part in joint programmes with public research laboratories, and particularly with universities.

It was the chemical industry at the end of the 19th century that first promoted a dynamic industrial research policy. During this period the first industrial research laboratories were set up in Germany, followed by the USA. Even before the Second World War, multinational corporations had started to decentralize their research work by setting up research centres outside their country of origin. The multinationalization of the global economy from the 1960s onwards enhanced this phenomenon, which was paralleled by the development of technological alliances between companies, in the form of licence exchanges, the setting-up of joint subsidiaries to exploit a given form of technology, and cooperation in joint R&D projects.

In the most industrialized countries, those of the OECD, some 60-75% of national R&D is carried out in industrial laboratories, partly financed by public contracts (particularly military ones), while in a certain number of countries, technical centres or associations uniting companies within the same area of business perform research work for the whole of the profession. This is particularly the case with sectors connected with long-established industries such as mechanical engineering, textiles and metallurgy.

The importance of the role of each of the protagonists in R&D in national systems of S&T greatly depends on the institutional customs in the various countries, their political and economic systems, and the part played by industry in the national economy. We can make a few broad comments on the subject. Those countries with an Anglo-Saxon background, and small European countries such as Switzerland, Austria and Belgium, have generally given considerable precedence to universities for basic research work. Universities have retained greater independence than other systems, and therefore have both the capacity and the will to define a research policy. This is especially so with the foremost American and British universities. In other industrialized countries and in many developing countries, a 'mixed' solution has been adopted. Basic research is carried out both by university laboratories and public research organizations with their own research laboratories and staff. In the countries of Eastern Europe, the science academies do most of the basic research, and university research work is generally very small in quantitative terms.

Most industrialized countries and a more limited number of developing countries have given major precedence within their national S&T systems to the public research organizations required for the exercise of state prerogatives regarding strategic assignments in the fields of defence, energy, transport and telecommunications. Nuclear energy, aerospace and military research are of course the most notable examples of sectors in which public organizations of this type have been set up, in connection with what is called the policy of major S&T programmes dedicated to the construction of new weapons systems (planes and missiles), nuclear reactors, Earth-observation and telecommunications satellites.

As for industrial research, it is developed above all in the companies of the most industrialized countries, mostly those of the OECD. Indeed, very few developing countries have companies with the financial resources to invest in industrial R&D, whereas the research budgets of multinational corporations often run into billions of dollars.

Institutions of S&T policy

Scientific research was only able to acquire its important and enviable social and political status, thereby obtaining the ever-increasing financial resources required for its development, when the modern state perceived its 'operational' value (with its wealth of potential applications), and recognized that it could also be the objective ally of political and economic power.

The Second World War saw the real turning point in relations between science, technology and political power. It became clear at that time that applied research programmes mobilizing hundreds of scientists enabled the attainment of targets deemed strategic in the military sense of the term, for example by developing new weapons systems (such as the atomic bomb or radar), and ensuring the replacement of basic raw materials by new industrial products.

For a modern state, S&T today represent an issue at three levels. The objective of research is to produce new know-how (in the natural and social sciences) in order to understand the world and society in which we live. This therefore constitutes a cultural issue. Technological innovation, as we have noted, forms the foundation for industrial development, while technological competitiveness for national enterprise is a key element in any state policy. S&T therefore represent, today, much more than a century ago, economic and social issues. Finally, research and technology increasingly evoke a strategic issue, in the sense that the control of S&T know-how is often vital in order to provide a nation or group of nations with the means for independence: the ability to communicate, and to ensure the supply of energy and of certain key raw materials. Hence the importance attached to research programmes on energy systems (nuclear power and thermonuclear fusion), on micro-electronics and information technology, telecommunications, space and oceanography.

Military research, of course, represents in itself a strategic issue that mobilizes large-scale resources in the USA, France, the UK, Russia and China, as well as in certain developing countries.

The growing awareness in almost every industrialized country, and in an increasing number of countries in the Third World, of the role now played by S&T in public policy, has led them to implement research and technology policies. By stating priorities, the policies aim to define development targets for national S&T work, to mobilize public and private research funds, to stimulate technological innovation and to decide on financial and human resource allocation. The policies also aim to implement national research programmes, with particular regard to sectors in which major economic, social or strategic issues are at play. They also promote international cooperation programmes.

National governments in every country therefore play a major role in the technological R&D system. Broadly speaking, they are concerned with three principal areas:

They define the main objectives for national policy in S&T (major options, top priorities) and the projects, orientations and operating modes of public research organizations and, to a lesser degree, sometimes of universities.

They define the level of finance for public research as well as the nature and volume of contracts signed with companies as part of public assignments with a research dimension. Public finance for research in developed countries stands at between 20% and 65% of the total national expenditure in R&D; in developing countries national research is very often financed exclusively by public funds.

They determine the fiscal, financial and legislative parameters for the entrepreneurial environment that will have a major influence on the corporate will and capability for research and innovation.

These three areas basically constitute a national policy for research, technological development and innovation.

In S&T, 'government' functions are being simultaneously exercised at different levels, extending increasingly from the traditional national level to the regional level. In this way, in a federal state such as Germany, the *Länder* play a very important role in funding public research organization work and providing backing for technology. The same is true of the USA, where individual states provide significant financial backing for technology. In France, since the application of the 1982 decentralization laws, the regional authorities also contribute financially to R&D operations; in China, the provinces and certain municipal authorities such as Shanghai provide significant financial backing for applied research institutes and technology projects.

At the European level, the R&D policy of the European Community (EC) occupies a major position in the financial decision-making hierarchy. It has a supranational character which has increasing weight in certain sectors and has no other equivalent anywhere else in the world. It is worth noting that in certain countries, ministerial departments have specific budgets (generally called 'incentive funds') designed to catalyse new research work or stimulate industrial research and innovation.

Globally, the role of government is that of a 'regulator' for the national system of research and technology, implying that it carries out the following functions:

Strategic analysis and predictions at the national level, i.e. analysing the internal strengths and weaknesses of the research and technological development system in terms of external threats and opportunities, both present and future (international competition, social requirements, etc.).

Evaluation of the work and operation of public research organizations, universities and research agencies.

Follow-up of the interfacing between the national system of research and technology and the industrial and educational sectors, other areas of state intervention (fiscal, industrial, social policy, etc.) and finally with society at large (over ethical questions for example).

By gradually becoming a 'state affair' in every country, S&T have led to the setting up of a network of institutions and government bodies enabling priorities to be stated, strategies to be developed, and the necessary decisions to be taken for the allocation of resources. As a result, in most countries there is an office at ministerial level whose purpose, in general terms, is to develop, impel and coordinate national S&T policy. The ministry, however, has a highly variable position in the government hierarchy.

In the USA, the presidential system tends to concentrate a number of functions coordinating activities vital to national policy within the Presidency. It is precisely the strategic nature of the numerous options in S&T programmes that led President Eisenhower to set up an Office of Science and Technology Policy at the White House, whose role has since been enhanced. While it does not manage programmes, the Office plays the role of a federal research bureau with considerable weight where decisions have to be made in terms of US national and international strategic options and priorities. In general, those countries which attach top priority to large-scale S&T programmes that imply detailed planning of the projects that have to be implemented, entrust the task of defining an overall research and technology policy to a powerful ministerial structure. (In the USA, 80% of the public R&D budget up until 1992 was dedicated to the major civilian and military programmes, a percentage equally high in France, the UK and Russia, but lower in Germany and Japan.)

Thus it is that in Germany and France a Ministry for

Research and Technology is responsible for national policy (together with universities in the case of France). In Japan, a Technical and Science Agency, whose director carries ministerial rank, has a similar role. The MITI (Ministry of Industry and Foreign Trade) nonetheless plays a specific role in promoting new technology, especially in Japanese industry. In the UK since 1992 the Minister for Science has been a Cabinet member, with a small department to carry out his duties (the Office of Science and Technology) placed under the responsibility of the Prime Minister's Scientific Adviser.

In Russia, a Minister for Research and Technology is responsible for S&T policy; in China the State Committee for Science and Technology carries out the same function.

In many countries ministerial responsibilities for research and technology are linked or attached to the Ministry of Education (or Universities) and Science, a Secretary of State for Scientific Research occasionally being delegated for all matters relating to science policy. This is the case in Italy, Spain and Algeria for example. In some countries, such as Portugal, the Ministry for Research is attached to the Planning Department, and sometimes directly to the Prime Minister.

PIERRE PAPON is Professor of Physics at the *Ecole supérieure de physique et chimie industrielle de Paris* and Director-General of the *Institut français de recherche pour l'exploitation de la mer* (IFREMER). He is President of the *Observatoire des sciences et des techniques* (OST) and a former Director-General of the *Centre national de la recherche scientifique* (CNRS).

REMI BARRE, civil engineer and economist, has been the Director of the *Observatoire des sciences et des techniques* (OST) since its creation in 1990. He has been director of an economics consulting firm and has worked for the Ministry of Research and Technology in France and taught at the *Conservatoire national des arts-et-métiers*.

BASIC SCIENCES AND INNOVATION

Keith Pavitt

The economic and social usefulness of basic research in modernizing societies was recognized long ago. Debate continues, however, about whether, how and why basic research is useful to the country that funds it.

At one extreme, we have advocates of the so-called linear model, who argue that scientific discoveries are the main source of technology, and of subsequent economic and social change. Scientists reveal the laws of nature and publish the results in papers, and engineers and business firms then transform them into useful physical artifacts. Outstanding examples are electromagnetism, organic chemistry and nuclear fission. Governments should provide generous support to basic research since, left to themselves, business firms would invest less than the optimal amount, given their short time horizons and inability to capture the full benefits of a published – and therefore freely available – output.

At the other extreme, the results of basic research are seen as at worst mostly useless, and at best available to anyone in the world who wishes to use them, since – once they are published – they become a 'free good'. A country's rate and direction of technological change are instead much more heavily influenced by economic and social conditions. Expenditure by national governments on basic research should therefore be considered as a form of conspicuous (cultural) consumption, to be compared with government expenditure on the arts, sport and similar activities. This is particularly the case in developing countries, where – it is argued by the same groups – the results of the world's basic research are published and freely available, and where local basic research is of inferior quality.

Commonly heard debates along these lines are misleading and often sterile, since they oversimplify the multiple and varied nature of the links between basic research and technological development. In particular, the former benefits the latter through the creation and transfer of the knowledge, skills, instruments and networks of professional contacts that make up much of the capacity to tackle complex problems, in addition to the creation and transfer of readily applicable written information. This has major implications for policy.

BASIC RESEARCH AND TECHNOLOGY AS INTERACTING SYSTEMS

Often implicit in the public debate is the view that the main 'outputs' of basic research and technological development are very similar forms of codified knowledge: basic research in the form of published papers; technological development in the form of patents, blueprints, operating instructions and software code. It is a view accorded academic weight through mainstream theories in both the sociology of science (Merton, 1942), and the economics of technology (Arrow, 1962).

However, recent studies show that, although basic research and technological development are strongly interactive, they differ in both purpose and nature. For purposes of understanding and prediction, basic research often simplifies, by creating 'ideal' laboratory conditions, or assuming 'other things being equal'. Technological development, on the other hand, is concerned ultimately with making products, processes and systems perform outside the laboratory in a world of multiple technological, economic and social interactions and constraints. These products, processes and systems are almost always too complex for their performance to be predicted confidently from theory (Kline, 1991). This is why the dominant activity in business firms is not research, but the much more costly design, development and testing of prototypes and pilot plant, together with production engineering and quality control. It is also why basic research and training have been established in a variety of engineering disciplines, precisely to train technological problem-solvers to integrate knowledge from a variety of disciplines in the development and use of complex technological systems, and to identify practical problems, the solution to which requires more fundamental scientific understanding (Rosenberg and Nelson, 1992).

DIRECT INTERACTION VARIES GREATLY

Broad generalizations about direct transfers of codified knowledge from basic research to technology are inevitably misleading, given major differences across fields and industries. This is confirmed by analyses of US patent documents which reveal how widely the frequency of patent citations to journal papers varies between industries (Narin and Olivastro, 1992). It is highest in the chemical and food processing industries (where citations are concentrated on basic research in chemistry, biology and clinical medicine), followed by instrumentation (citations spread fairly evenly across pure and applied research in all fields), and electrical and electronic products (citations concentrated in applied research in physics and engineering). Interestingly, the transportation sector (including aerospace and automobiles) has the lowest frequency of patent citations to journals (concentrated in applied engineering), showing that the results of basic scientific research do not make a strong direct contribution to the design, testing and operation of the complex machine systems that predominate in these sectors.

INDIRECT INTERACTIONS ARE MORE IMPORTANT

However, it would be misleading to assume that patent citations reflect all – or even most – of the contributions of basic research to technological development. Past studies suggest this comes through the transfer of largely uncodified (tacit) knowledge and skills, embodied in the problem-solving capacities of researchers, their instruments, and the often informal networks of professional contacts that they develop in the course of their work (Gibbons and Johnston, 1974; Irvine and Martin, 1980). A survey of the opinions of more than 600 US industrial R&D directors shows that three-quarters of the most important contributions of academic research to technological development were in the form of uncodified knowledge and skill transfers, and only one-quarter in the form of codified knowledge (Nelson and Leaven, 1986; Nelson, 1987). Codified knowledge transfers tended to come from more applied disciplines (computer science, materials science or metallurgy) and were applied in relatively few industries. Useful uncodified knowledge and skills, on the other hand, came from a wider range of disciplines, and had a more pervasive effect.

IMPLICATIONS FOR ANALYSIS AND POLICY

These advances in our understanding of the links between basic research and technological development have major implications for analysis and policy.

The nature of the benefits of basic research

Contrary to common belief, the main economic benefit of basic research is not knowledge directly applicable in a narrow range of sectors, but background knowledge, research skills, instruments and methods that yield economic benefits over a much broader range of sectors. Amongst other things, this poses a challenge to analysts and policy makers who continue to assume that the main (or sole) economic 'output' of basic research is information that is easy and virtually costless to apply, rather than an irreplaceable input into a more costly and complex process of technological development (Pavitt, 1991).

This has major implications for policies in developing countries. In particular, it shows that the results of basic research are not freely applicable, but must be assimilated into complex technological systems through the creation of an indigenous problem-solving capacity closely linked to international professional networks. This will require policies to establish university research capacities – probably in the basic engineering disciplines – and to encourage foreign postgraduate training, to improve quality and (more importantly) the joining of international professional networks. And since the economic benefits of basic research flow mainly through personal contacts and movements, this basic research is more likely to be economically useful if it is closely linked to higher education and related research training.

Does the home country benefit from its investment in basic research?

In the light of the above, it is also hard to sustain the assertion that basic research brings no extra benefit to the country funding and performing it. A large portion of the economic and social benefits of basic research are embodied in trained scientists and engineers, including some with a proven research competence. Such people will be employed locally by business firms and other technological practitioners, provided these have a strong incentive to improve their problem-solving abilities. Experience in the developed countries shows that this requires outward-looking policies encouraging international competitiveness, and support for business firms to fund and perform their own technology-improvement activities.

Given that firms cannot capture all the economic benefits from funding such activities (if only because trained labour can change employment), some public subsidy to private firms may be economically justified. This is certainly the case for basic research and related training, where individual firms cannot realistically be expected to fund activities of general benefit to local business.

Whatever the specific policy, the general objective should be the creation of problem-solving technological capacities in business firms and wherever else they are required (Bell and Pavitt, 1993). Without these capacities the demand for basic research, related training, and currently fashionable measures like 'science parks', will wither and die.

KEITH PAVITT is R.M. Phillips Professor of Science and Technology Policy Studies at the Science Policy Research Unit (SPRU), University of Sussex, UK. He studied engineering, industrial management and economics at Cambridge and Harvard, and then worked at the Organization for Economic Cooperation and Development (OECD) in Paris. During his 20 years at SPRU, he has published widely on the management of technology, and science and technology policy. Professor Pavitt advises numerous national and international bodies on policies for technical change and is a main editor of *Research Policy*.

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INDICATORS: PURPOSE AND LIMITATIONS

Rémi Barré and Pierre Papon

Science and technology indicators are quantitative units of measurement of the parameters defining the status and dynamics of research and technology systems. Possible uses for these indicators are highly diversified: as a national overview for science policy makers or legislative authorities, strategic analyses for decision taking by research institutions, S&T surveys, programme evaluation, etc. An increasing number of leaders in S&T are thus confronted with decisions and choices which have to be based on such indicators.

The need for indicators led to the setting up in the 1960s of annual surveys on industrial and public research. In the early 1970s, the National Science Foundation (NSF) in the USA began publishing the twice-yearly series of *Science and Engineering Indicators*. Parallel to this, the OECD undertook to harmonize its surveys and indicator production work on an international scale to enable their comparability, and for this purpose drew up the *Frascati Manual* which lays down the concepts and codifies the survey methods.

In the second half of the 1980s, the demand for indicators became more diversified, just at the time when it became possible to exploit sources of new information. More and more surveys attempting to produce quantitative data were initiated as part of evaluation and strategic orientation work, and as part of community programme management. As a result, a certain number of countries have been led to upgrade their permanent system of quantitative data production on S&T. In France, for example, the *Observatoire des sciences et des techniques* (OST) was created in 1990 with this purpose in mind.

A feature of the last few years has been the fact that the strong demand for indicators from the public authorities and industry – which had existed for many years – can now be matched by an enhanced capacity for data production and supply. This is due to international efforts towards statistical harmonization, to the development of new methods for producing indicators (bibliometry) and, more generally, to the continual improvement in electronic means of data storage, access and processing.

THE INDICATORS USED IN THIS ARTICLE

In reality there is a whole host of possible indicators, but an S&T indicator can be delineated by any of the following criteria:

- The object and parameter under measurement: people (research scientists, teacher-researchers, engineers, research support staff, where necessary with qualifications, age, sex, disciplinary specialization, etc.); financial resources (operating, investment, received from state budgets or obtained by outside contract); 'codified' knowledge (scientific publications or patents, qualifications obtained); and 'embodied' knowledge (instruments, components or technology-intensive capital goods purchased or sold, imported or exported).
- The space within which the parameter is measured: institution (laboratory, company, public establishment, university, etc.) or territory (town, region, nation, plurinational area).
- The type of work under measurement: discipline or scientific area, field or technological specialization, sector or industrial branch, target for public policy, type of research (basic, finalized, development).
- The scale of measurement: micro- (decision-taking body, company, laboratory, or university scale), meso- (discipline, field or sector scale), or macro- (territorial scale).
- The type of measurement: stock parameter, which measures a volume (or level), or relational parameter (flow or relation) between two entities.

The indicators used in this world overview must make international or interregional comparison possible. We have therefore adopted indicators basically measuring volumes on meso- or macro-scales, concerning scientific disciplines, technological fields and industrial sectors, at national and plurinational levels.

In this section we present three types of indicators, which we shall briefly examine.

Resources dedicated to S&T activities – input

The measurement of resources is made at the level of each country by national surveys on R&D expenditure and scientific staff. The results of these surveys are then reprocessed and published by various international institutions, in particular OECD, UNESCO and the Commission of the European Communities. Several tables presented here are based on data published by these organizations.

Measurement of scientific publications – output

Scientific activity is measured by its production of scientific publications (science bibliometry). A publication is indeed a basic product of scientific work but, as we have seen, it is not the only one: science also generates other forms of 'product', for example higher education or technical expertise. The indicator therefore focuses on one specific aspect of scientific research.

Indicators have been calculated using the database of the *Science Citation Index (SCI)* established by the Institute of Scientific Information (ISI), based in Philadelphia, USA. Each publication is assigned to the country of address of the authors' laboratory. If there are several authors from different countries (for example three), each country is assigned a fraction of the publication (one-third in this example); this is known as 'fractional' counting. The 3 500 science journals whose publications are indexed in the ISI database are classified into eight disciplines. The processing therefore consists of counting the fractions of papers per year, per country and per discipline. The basic problem here is the sheer volume of data that has to be processed if one wishes to establish a world overview: the *SCI* catalogues some 600 000 publications per year. It is also possible to construct impact indicators (the number of citations received per paper in relation to the world average) and country co-publication indicators (the relative number of publications co-signed by authors from different countries).

Measurement of technological production by patents – output

Technological activity is measured by its patent production (patent bibliometry), which indicates the level of inventiveness and creativity in technology for industrial purposes.

The indicators have been calculated on the basis of European patents (patents which hold on the single European market), and on American patents (patents which hold on the US market). Since these two markets are the largest and the most open to competition, we may consider that the patent decisions taken on them are representative of the technological capabilities and innovation of industrial firms at a global level. Here again, indicators must permit a world overview, which requires the processing of all the data in each database, with some 40 000 patents granted in Europe each year, and some 80 000 in America. We have again used fractional counting of the inventors, according to the country of their address. The patents have then been classified into fields of technology based on the International Patent Classification (IPC).

INDICATOR LIMITS

It is essential to have an appraisal of indicators and their reliability from two points of view. The first is that of the validity of the underlying conceptual models; the second concerns the relation between what one aims to measure and what is measured in reality: this is the evaluation of the technical inadequacy of the statistical production process from the individual data to the indicators. Let us look at these two dimensions in turn.

Conceptual appraisal

The construction of indicators relies on the choice of parameters which, explicitly or not, refer to the underlying conceptual models of the science/technology/society system. These choices take place at every stage in the indicator production process: at the level of data gathering on each firm, research institution, publication or patent, a choice is made of the aspects we decide to take into account; at the level of systematic statistics, a choice is made in terms of the geographical and thematic categories and classifications we use; finally, at the indicator construction stage, choices are made to decide which are the meaningful relations between the various parameters for characterizing the situation. These choices are based, either explicitly or implicitly, on hypotheses about the way in which the science/technology/society system 'works', i.e. on a conceptual model.

The problem is that in order to make these choices we do not always have the understanding or the information we need. Accounting for phenomena of technology dissemination or of science/technology relations comes up against precisely this type of difficulty. It is here that research work on the economics of technical change, on industrial economics, on innovational sociology, and on science policy, meets the concerns of those who have to construct S&T indicators.

Conversely, it may also be that pertinent ideas have to be cast aside for lack of any means of measuring them. In this way, for example, one of the major tasks for scientists in any country is the performance of scientific appraisal and the provision of technical expertise for the public authorities; unfortunately there is no method of measuring this activity in an internationally comparable way.

Technical evaluation

For resource indicators, the difficulties stem on the one hand from the definition of what is a research activity and what is a researcher, which can vary considerably from one country to another (the definition was extremely broad in the former USSR, for instance); the problem has only been partially solved with the publication of the *Frascati Manual* by the OECD, which gives definitions of the terms required as precisely as possible. On the other hand, the problems stem from the absence of reliable exchange rates in 'purchasing power parity' for many countries, which means uncertainty in the conversion to a single currency for international comparison. Another point is that resource indicators make little or no distinction between the disciplines of science and technology.

For indicators of scientific production (publications), the evaluation consists of questioning the representativeness of the science journals used in the database in question, in this case the *SCI*. Despite the 'objective' nature of the selection of science journals in this database (their reputation, measured by the average citation index received by the publications in each journal), it is clear that the journals of developed countries are over-represented and particularly those of English-speaking countries. It is 'dominant' science which is measured here, and the work of developed countries is better accounted for than that of others.

For indicators of technology production as measured by patents, the evaluation does not concern the databases (they are exhaustive and exact), but the interpretation that can be made of the indicators: the registration of patents is, all other things being equal, less intense in certain companies and in certain countries, according to their strategy or markets. The patent indicator is representative of the activity of firms wishing to export using the competitive advantage that an innovation can bring. In other words, it gives more credit to the activity of firms in developed countries, particularly since it only considers patents granted in the USA and Europe.

It is important to remember that each indicator merely represents one facet of reality (and even then only partially): resource indicators say nothing about results; scientific publication indicators say nothing about work in training or technical expertise; and patent indicators say nothing about technological fields in which no patents are granted, nor do they say anything about the use of the patent for innovation. It is clear that indicators only have meaning when considered together, since it is obvious there can be no single unit of measurement for so complex a system.

Despite all their limitations, current indicators may be considered to give correct scales of magnitude for the parameters they measure and, when considered as a whole, to give a fairly reliable representation of reality.

GLOBAL OVERVIEW

Rémi Barré and Pierre Papon

FINANCIAL AND HUMAN RESOURCES

We can give a world overview of research and development (R&D) activity on the basis of estimates of financial backing (Table 1). This shows that the countries of the OECD zone alone produce 80-88% of world R&D, depending on how R&D is accounted for in the former USSR. We can therefore state that more than four-fifths of the global scientific research and technological development effort is made by the developed countries of the West and

TABLE 1
GROSS DOMESTIC PRODUCT (GDP), GROSS DOMESTIC EXPENDITURE ON RESEARCH AND DEVELOPMENT (GERD) AND GERD/GDP RATIOS FOR DIFFERENT AREAS OF THE WORLD (1990)

	GDP[1]	GERD[1,2]	GERD/GDP (%)
EC[3]	5 110	101.9	2.0
EFTA[4]	571	12.3	2.2
C&EE[5]	332	5.7	1.7
Israel	45	0.8	1.7
Former USSR[6]	1 673	18.9/56.9	1.1/3.4
USA	5 392	149.2	2.8
Canada	512	7.2	1.4
Latin America	715	2.9	0.4
North Africa	154	0.4	0.3
Middle and Near East[7]	526	1.9	0.4
Sub-Saharan Africa	257	0.7	0.3
Japan	2 180	67.0	3.1
NICs[8]	499	8.2	1.6
China	442	3.6	0.8
India	308	2.5	0.8
Other countries in Far East	277	0.5	0.2
Australia / New Zealand	340	3.9	1.2
World total	**19 334**	**387.7/425.7**	**2.0/2.2**

1. The monetary unit is 1 billion current US dollars (G$) calculated on parity purchasing power (ppp) for the countries of the OECD, or calculated based on the exchange rate for the other countries.
2. Gross domestic expenditure on R&D (GERD) measures the spending of all R&D activities on the national territory, all sources of finance combined (including those from overseas).
3. Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxemburg, Netherlands, Portugal, Spain, UK.
4. Austria, Finland, Iceland, Liechtenstein, Norway, Sweden and Switzerland.
5. Countries of Central and Eastern Europe.
6. Measuring the GDP and the GERD of the former USSR poses a problem of consistency with its accepted definitions at international level: we have chosen to give a high estimate, corresponding to the usually published figures, which is based on a wide interpretation of the notion of R&D, and a low estimate – three times lower than the previous figure – corresponding approximately to the OECD definition of R&D (sources: CSRS and IMEMO). Since we do not have a purchasing power parity exchange rate, we have used the 1989 exchange rate to which we have applied the deflation rate for the dollar between 1989 and 1990.
7. From Turkey to Pakistan.
8. Newly industrialized countries of Asia (Republic of Korea, Malaysia, Hong Kong, Singapore, Taiwan).

Note: OECD figures have been used for OECD countries, UNESCO figures for the others; for countries absent from UNESCO statistics, we have extrapolated from countries for which we have data and which are similar from the economic point of view.

Source: OST, based on OECD and UNESCO data (OST, 1993).

Japan (broadly speaking, the countries of the OECD); this is characteristic of a highly inegalitarian situation, even more so than gross domestic product (GDP) distribution.

Domestic R&D expenditure compared to GDP is an indicator of research 'effort rate'. In 1990 Japan was in the lead, devoting 3.1% of its GDP to R&D. It was followed by the USA (2.8%), the countries of the European Free-Trade Association (EFTA) (2.2%) and of the European Community (2%). Estimates are more difficult to make for the former USSR: if we use the data traditionally supplied, corresponding to a broad definition of R&D, we obtain a relative rate of expenditure which exceeds that of all the other countries (3.4%); if we use a definition closer to those used worldwide, the effort rate then becomes intermediate between that of developed countries and that of developing countries (1.1%).

In developing countries, national expenditure on R&D is significantly lower than 1% of their GDP. China, for example, despite its long scientific heritage, dedicates 0.7% of its GDP to R&D, according to official figures. In the poorest countries, only a small fraction of national income, something of the order of 0.2-0.4%, is dedicated to S&T. Worth noting, however, is the fact that the newly industrialized countries (NICs) of Asia already have a higher effort rate than certain countries within the OECD.

The analysis of R&D resources in terms of research workers and engineers gives a different panorama (Table 2). The countries of the OECD when viewed in this light only account for a little more (58%) or a little less (47%) than half the world total, depending how figures for the former USSR are calculated.

TABLE 2
R&D SCIENTISTS AND ENGINEERS AND POPULATION RATIOS FOR DIFFERENT AREAS OF THE WORLD, 1990

	R&D scientists and engineers ('000s)	Population (millions)	Scientists per 1 000 population
EC[1]	611.4	327.2	1.9
EFTA[1]	72.3	32.1	2.2
C&EE[1]	263.5	124.0	2.1
Israel	20.1	4.6	4.4
Former USSR[2]	465.7/1 397.0	288.0	1.6/4.9
USA	949.3	251.5	3.8
Canada	62.5	26.6	2.3
Latin America	162.9	296.7	0.5
North Africa	38.1	152.5	0.3
Middle and Near East[1]	19.0	301.6	0.1
Sub-Saharan Africa	35.0	494.3	0.1
Japan	582.8	123.5	4.7
NICs[1]	92.3	89.6	1.0
China	410.5	1 135.5	0.4
India	119.0	853.4	0.1
Other countries in Far East	99.7	585.9	0.2
Australia / New Zealand	47.5	20.5	2.3
World total	4 051.7/4 983.0	5 107.5	0.8/1.0

1. See Table 1 for definitions.
2. For the former USSR we have applied a ratio of 3 to 1 to the published number of scientists and engineers, in order to comply with OECD definitions (see note 6 on Table 1).

Note: The figures for OECD countries are those published by OECD, those for other countries are taken from UNESCO data.

Source: OST, based on OECD and UNESCO data (OST, 1993).

When compared to the population, the figures make a distinction between developed countries (with a ratio higher than or equal to 1.9 per 1 000, rising to 4.7 for Japan) and developing countries (with a ratio ranging between 0.1 and 0.5 per 1 000). The situation of the former USSR is once again difficult to analyse: its ratio is either the highest in the world, or in an intermediate position, depending on whether one adopts the extensive or international definition of what R&D activity actually entails.

TABLE 3
SCIENTIFIC PRODUCTION (PUBLICATIONS)[1] IN DIFFERENT AREAS OF THE WORLD, 1991

	World share[2] 1991 (%)	1991[3] (base 1983 = 100)
EC[4]	27.7	103
EFTA[4]	4.4	98
C&EE[4]	2.3	91
Israel	1.0	89
Former USSR	6.4	79
USA	35.8	96
Canada	4.4	107
Latin America	1.4	117
North Africa	0.4	113
Middle and Near East[4]	0.6	180
Sub-Saharan Africa	0.9	96
Japan	8.0	117
NICs[4]	1.0	309
China	1.1	128
India	2.0	57
Other countries in Far East	0.1	67
Australia / New Zealand	2.7	92
World total	100.0	100

1. Scientific production by country is measured by counting the number of scientific publications of scientists whose laboratory is located in each country. The indicators presented here have been calculated by the OST using the *Science Citation Index (SCI)* database produced by the Institute for Scientific Information (ISI).
2. The indicator presented here is the percentage share in the world total for each zone, all disciplines combined.
3. Share of 1991 divided by the share of 1983, multiplied by 100.
4. See Table 1 for definitions.

Source: OST, based on *SCI* data (OST, 1993).

S&T PRODUCTION IN DIFFERENT AREAS OF THE WORLD

As an instrument for measuring S&T activity, the indicator of publications probably gives us a slightly deformed vision of reality in that it accounts poorly for the results of research work published in science journals issued in the countries of Eastern Europe or the Third World. Thus, the *Science Citation Index* (*SCI*), the leading tool for the bibliometric basis of the global distribution of scientific production, only considers a small number of science reviews published in developing countries amongst the 3 500 science journals it analyses. In countries whose scientific population is relatively large, such as Argentina, Brazil or China, only a very minor number of scientific reviews are represented in the database, although various surveys have highlighted the significant quantity of research carried out in developing countries in fields of particular importance to them, such as tropical agronomy and soil science.

Similarly, the procedure for the granting of patents in the USA and in Europe is not easily accessible to inventors or companies from Third World countries, in addition to the fact that it is expensive. A whole range of appropriate technology for developing countries therefore lies outside our scope of analysis. The same is true for countries of Eastern Europe. Macroscopic indicators therefore almost certainly under-represent S&T production in countries outside the OECD zone. Clearly, what is measured here is 'mainstream' S&T production, which is by no means all of science and technology, though a significant part.

Scientific publications

The publication indicators for world science production confirm the very strong impression of inequality in the production of knowledge already suggested by the examination of R&D expenditure (Table 3). We find that 40.2% of scientific publications are produced by scientists from North America (mostly from the USA) and 34.4% by European scientists (East and West). The remaining 25.4% are shared by Japan (8%), the former USSR (6.4%), other industrialized countries (3.7%) and the NICs (1%). The developing countries of Africa, Latin America and Asia account for about 6.5%.

TABLE 4
SCIENTIFIC SPECIALIZATION BY REGION, 1991[1]

	Europe	Former USSR	North America	Latin America	Muslim countries[2]	Sub-Saharan Africa	Industrial Asia[3]	Other countries of Far East	Australia/ New Zealand
Clinical medicine	1.13	0.40	1.05	0.88	0.78	1.34	0.81	0.46	1.17
Biomedical research	1.02	0.61	1.12	0.92	0.54	0.65	0.97	0.44	0.87
Biology	0.82	0.40	1.14	1.61	1.27	2.47	0.85	1.08	2.19
Chemistry	1.00	2.08	0.70	0.84	1.70	0.59	1.42	1.80	0.60
Physics	0.95	2.10	0.83	1.30	0.76	0.32	1.17	1.81	0.45
Earth and space sciences	0.86	1.25	1.16	1.31	1.07	1.53	0.41	1.10	1.47
Engineering sciences	0.77	1.17	1.04	0.60	1.74	0.56	1.56	1.51	0.69
Mathematics	0.90	0.51	1.28	0.98	0.94	0.46	0.60	1.15	0.76
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

1. The indicator presented here is the specialization index for eight scientific disciplines: it is the ratio of the country's world percentage share of publications in one discipline against the world percentage share of the country all disciplines combined (an index figure higher than unity indicates the relative strength/specialization of the country, and its relative weakness/lack of specialization if the figure is less than unity).
2. North Africa and Middle Near East.
3. Japan and NICs.

Source: OST, based on *SCI* data (OST, 1993).

In eight years, from 1983 to 1991, the major growth area has been Japan, the NICs and China: these countries together accounted for 7.4% of the world share in 1983, and for 10.1% eight years later, representing a one-third increase. Significant growth is also identified in the Middle and Near East, but from a lower starting point. North Africa and Latin America are also gaining ground, albeit at a slower pace. Apart from Japan, Canada and the EC, all the industrialized countries are seeing their share reduced, as are the former USSR and India.

Regions of the world exhibit specialization in terms of scientific production (Table 4). Europe is strong in clinical medicine, is well placed in biomedical research, chemistry, and physics, but appears to be weak in the engineering sciences as well as biology. The specialization of industrial Asia is quite different: weak in the life sciences, earth and space sciences and mathematics, but strong in physics, chemistry and engineering. The specialization of North America is almost exactly the opposite. The developing countries share, on the whole, specialization in biology and earth and space sciences, and a weak position in clinical medicine and biomedical research.

Patents granted

It is possible to evaluate world technology production, at least to a first approximation, using the indicator representing the patents granted both in the USA and in the European systems (Table 5). What is immediately striking is the quasi-total absence of countries outside the OECD: these account for only 1.6% and 2.7% of patents granted in Europe and the USA respectively. The USA in 1991 was responsible for a quarter of the world total of patents granted in Europe, and more than half those granted in the USA itself. The situation is mirrored in Western Europe (EC plus EFTA), with a quarter of the patents granted in the USA and nearly half those granted in Europe, while Japan represents nearly a quarter of the world total in each of the two systems.

Scrutiny of these developments highlights two phenomena: the rising power of Japan, and that of the newly industrialized countries in Asia.

S&T production and GDP

The index of scientific publications to GDP shows that, on

TABLE 5
SHARE OF DIFFERENT AREAS OF THE WORLD OF PATENTS GRANTED IN EUROPE AND THE USA, 1991 SHARE AND 1991 WITH BASE 1981 OR 1986 = 100

	European patents[1,3]		American patents[2,3]	
	World share 1991 (%)	1991 (base 1986 = 100)	World share 1991 (%)	1991 (base 1981 = 100)
EC[4]	42.6	92	20.1	90
EFTA[4]	5.8	82	3.6	81
C&EE[4]	0.3	71	0.2	66
Israel	0.4	122	0.4	124
Former USSR	0.1	51	0.2	102
USA	24.7	93	45.6	95
Canada	0.6	62	2.4	113
Latin America	0.1	139	0.2	102
North Africa	0.0	ns	0.0	ns
Middle and Near East[4]	0.0	ns	0.0	ns
Sub-Saharan Africa	0.1	67	0.1	89
Japan	24.4	149	25.0	120
NICs[4]	0.5	246	1.5	338
China	0.1	119	0.1	765
India	0.0	ns	0.0	ns
Other countries in Far East	0.0	ns	0.0	ns
Australia/New Zealand	0.2	23	0.6	94
Total	100.0	100	100.0	100

1. The database on European patents records the patents 18 months after application, whether granted or not at that date. For simplicity we shall refer to them as 'patents granted', especially since in practice world shares of countries are not significantly different.
2. Patents granted.
3. The granting of patents is used as an indicator of the technology production of a country: a patent is attributed to the country of address of the inventor. The indicators are calculated according to patents granted in the USA ('American patents') and in Europe, or more specifically via the European Patent Office ('European patents') enabling simultaneous grant of the patent in several European countries.
For American patents, and for patentees of American nationality (i.e. with an American address), we have counted companies and institutions, but not individual patentees. This is a means of attenuating the 'home advantage' of Americans in the grant of American patents.
The indicators for American patents are based on work by CHI-Research Inc. on the database of the US patent office (USPTO); the indicators for European patents have been calculated using the bibliometric EPAT database, built from the EPAT database of European patents, drawn up by the French patent office (INPI).
European patent indicators have only been calculated from 1986 onwards, since this is the year when the 'European channel' for the granting of patents was generalized, and therefore became representative of technological activity.
4. See Table 1 for definitions.

ns: non-significant number.

Source OST, from EPAT and CHI-Research – USPTO data (OST, 1993).

the whole, industrialized countries are more 'scientifically intense' than the others (Table 6). Israel, the EFTA countries, Canada, Australia and New Zealand have particularly high indices. The USA, the C&EE countries and the EC are a little behind. The index of India deserves special mention for being well above average, as does the index of Japan for being significantly below average. On this index, Africa, Latin America, China and the NICs are about 50% below average, close to Japan and the former USSR.

Turning now to patent production in relation to GDP

TABLE 6
INDEX OF SCIENTIFIC PUBLICATIONS AND PATENT PRODUCTION RELATED TO GDP, 1991

	Index[1] to GDP of		
	Scientific publications	European patents	American patents
EC[2]	105	161	76
EFTA[2]	150	196	121
C&EE[2]	131	17	13
Israel	433	172	172
Former USSR	73	1	2
USA	128	89	163
Canada	166	23	90
Latin America	25	3	5
North Africa	48	ns	ns
Middle and Near East[2]	21	ns	ns
Sub-Saharan Africa	66	8	10
Japan	71	216	221
NICs[2]	40	19	58
China	46	4	4
India	128	ns	ns
Other countries of Far East	9	ns	ns
Australia / New Zealand	151	11	34
World	**100**	**100**	**100**

1. World average set at 100. The index of the S&T production of a country related to its GDP is a measure of its national scientific or technological intensity. The numerical value of the ratio is not significant in itself, which is why it is expressed as a function of base 100 for the world average, which also makes international comparisons easier.

2. See Table 1 for definitions.

ns: non-significant number.

Source: OST, based on EPAT and CHI-Research - USPTO data (OST, 1993).

(Table 6) we can see that Japan has achieved the best performance worldwide both in EC patents and in US patents, thus overtaking both Americans and Europeans on their own territory. The NICs, in American patenting, are getting close to EC countries, having already passed countries like Australia and New Zealand. The overall performance of EFTA countries and Israel deserves mention.

S&T WORLD OVERVIEW

Given the macroscopic data available on global scientific activity, one fact is clear: the three geographic units making up the 'Triad' (the USA, Japan and the 12 countries of the EC) together concentrate almost three-quarters of the world potential for the production of S&T knowledge. The Triad, with which the EFTA countries can be considered, has a rhythm of S&T development which is more or less homogeneous despite major differences in individual countries' R&D expenditure and strategies. Central and Eastern Europe and the countries of the former USSR, whose scientific potential is high, are currently going through a radical process of reorganization against a highly unfavourable economic background. While these former Socialist countries, together with the developing countries, form a heterogeneous group whose contribution to the production of S&T knowledge is significant, they have

TABLE 7
GROSS DOMESTIC EXPENDITURE ON RESEARCH AND DEVELOPMENT (GERD) IN THE TRIAD, 1990 – COMPARATIVE % BREAKDOWNS OF FINANCING AND IMPLEMENTATION

	EC (%)	USA (%)	Japan (%)	Total (%)
GERD financing				
State/civilian	36.2	18.5	25.4	25.6
State/military	11.5	30.9	1.5	18.5
Industry	52.3	50.6	73.1	55.9
Total	100.0	100.0	100.0	100.0
GERD implementation				
State	18.9	14.1	11.6	15.1
University	16.3	16.0	17.6	16.4
Industry	64.8	69.9	70.8	68.5
Total	100.0	100.0	100.0	100.0

Source: OST, OECD data (OST, 1993).

great difficulty in keeping up with the rhythm of the most industrialized nations.

COMPARISONS BETWEEN THE USA, THE EC AND JAPAN

The financing and implementation of R&D

While the countries of the Triad belong to the same market economy system, they nonetheless have widely differing traditions and practices regarding the role of the state in economic development, and therefore its role in technology policy. This is why the percentage of GERD financed by the state (for civilian and military purposes) in 1990, ranges from 27% in Japan to nearly 50% in the USA (mostly military R&D) and in the EC (mostly civilian R&D) (Table 7). In other words, 73% of Japanese GERD is financed by firms, which shows the importance attached by Japanese industrial corporations to their R&D strategy, as a way of controlling both the technology and their markets. A ministry such as the MITI has helped Japan to define common policies for both private enterprise and the Japanese state agencies in sectors considered to be a priority, such as electronics. The differences are less marked within the Triad, though, if we compare the share of GERD which is carried out (but not necessarily financed) by the corporate sector: it ranges from 65% in the EC to 71% in Japan, and stands at 70% in the USA. It is therefore in Europe that the role of the state is most marked in R&D execution, via public research organizations and universities; a historic tradition of state intervention (strongest in France) carries all its weight in the orientation of national research policies.

Also worthy of note is the fact that certain countries such as the USA, the UK and France within the Triad, as well as Russia and China outside it, have, for political reasons, given a high degree of priority to military research. The major technology programmes launched during the 1950s in the USA (to a certain extent following on from the Manhattan Project to build the atomic bomb during the Second World War), in the former USSR, then in the UK, France and China, were the result of the need to base the arms race on scientific discovery and technological innovation. Unlike the other major industrialized countries, Japan and Germany, with no effective access to nuclear weapons, launched no broadscale military research efforts. It is therefore not surprising to note, within the Triad, major discrepancies between percentages of R&D funds dedicated to research for defence purposes: in the USA, in 1990, 63% of public R&D funds were dedicated to

TABLE 8
COMPARATIVE SHARE OF THE TRIAD SECTORS IN EUROPEAN AND AMERICAN PATENTING

	European patents world share (%)		American patents world share (%)		
	1986	1991	1981	1986	1991
EC	46.5	42.6	23.4	22.3	20.1
USA	26.5	24.7	52.7	48.0	45.5
Japan	16.3	24.4	14.3	20.8	25.0

Source: OST, EPAT bibliometry, CHI-Research data, USPTO (OST, 1993).

military research, while the percentage was only 24% for the EC (it reached 50% in the UK and 34% in France), and only 6% for Japan. While it is certain that countries such as Russia and China devote quite considerable resources to military research, precise figures are unavailable. The geographical distribution of research efforts is quite clearly outlined by military-based R&D. It sharpens the contrasts within the Triad and, more generally, between countries. On the whole, efforts in military R&D take the form of public contracts which are carried out by industrial corporations belonging primarily to two sectors: the aerospace and electronics industries.

Patent specialization and the evolution of technological strengths

A glance at developments during the 1980s shows the extraordinary progress of Japan in its patenting, both in Europe and in the USA (Table 8). The EC and the USA are losing their share in both the European and the American patent systems.

Examination of the Triad sectors per technological field (Table 9) shows that in Europe, Japan is the leading patentee in electronics and electrical goods, and comes a close second to the EC, level with the USA in the field of instrumentation. Analysis of the trends during the 1980s reveals the increased specialization of Japan in these fields. In Europe, the USA is powerful in instrumentation, chemicals and pharmaceuticals. The EC, in Europe, is powerful in the fields of industrial processes, machinery, mechanical engineering and consumer goods, but weak in electronics and electrical goods.

The relative positions in the American patent system (Table 9) confirm the Japanese specialization in electronics and electrical goods (more than a third of all patents) and in instrumentation; the weakness of the EC in these two fields is also confirmed, though the community does lead Japan in chemicals, pharmaceuticals and industrial processes.

INTERNATIONAL MOBILITY OF STUDENTS

Worldwide, 1.2 million students study in a university abroad: the international mobility of students is a massive phenomenon. Such mobility makes it possible for students of less advanced countries to have access to adequate higher education facilities, but it can also carry the risk of 'brain drain'; in any case, it serves to reinforce worldwide scientific networks and efficiently disseminates scientific knowledge.

Zones of origin: students going abroad

There are about 61 million students in the world, 2% of whom study in a foreign country (Table 10). The following geographical zones send the most students abroad: Middle and Near East, North Africa, Sub-Saharan Africa, the NICs and China. The EC and EFTA also have significant numbers of their students in a foreign country, but it is usually another European

TABLE 9
SHARE OF PATENTS GRANTED PER TECHNOLOGICAL FIELD, 1991

EUROPEAN	European patents world share (%)			1991 (base 1986 = 100)		
	EC	USA	Japan	EC	USA	Japan
Electronics, electrical goods	30.4	27.7	36.7	75	93	155
Instrumentation	35.6	28.6	28.1	88	93	157
Chemicals, pharmaceuticals	39.4	29.4	24.3	99	90	129
Industrial processes	47.4	23.7	18.4	98	94	130
Machinery, mech. eng.	55.5	17.9	16.9	98	96	146
Household consumption, civil eng.	60.3	15.8	8.7	102	93	151
Total (all fields)	42.6	24.7	24.4	92	93	149

Source: OST, EPAT data (OST, 1993).

AMERICAN	American patents world share (%)			1991 (base 1986 = 100)		
	EC	USA	Japan	EC	USA	Japan
Electronics, electrical goods	14.2	45.5	34.4	83	89	111
Instrumentation	16.1	45.8	30.4	86	99	115
Chemicals, pharmaceuticals	24.8	48.1	19.9	103	94	122
Industrial processes	22.8	47.5	19.1	93	96	115
Machinery, mech. eng.	23.8	41.6	23.6	91	97	106
Household consumption, civil eng.	20.3	47.6	12.4	93	94	120
Total (all fields)	20.1	45.5	25.0	90	95	126

Source: OST, CHI-Research – USPTO (OST, 1993).

country: we have here the phenomenon of intrazone mobility. In terms of the proportion of students going abroad (the 'expatriation rate'), Sub-Saharan Africa comes first, with a rate of 14%, followed by North Africa, and the Middle and Near East, with rates close to 7%. The NICs and China also have rates well above average. The USA, the former USSR and the C&EE countries have the lowest rates. Students from developing countries represent 40% of the world total, but they represent 70% of those studying in a foreign country.

Zones of destination: students received from abroad

The USA is the country which receives the largest number of foreign students by far (Table 11): more than 400 000, which is more than one-third of the world total of internationally mobile students, whereas they generate only 2% of that flux themselves. The next most important recipients are France, Germany and the UK, in that order; these three countries together receive 75% of the number of students received by the USA. Just behind the UK comes the former USSR, with a declining number of students received.

TABLE 10
INTERNATIONAL MOBILITY OF STUDENTS FROM DIFFERENT GEOGRAPHICAL ZONES, 1990

	Total student population ('000s)	Students studying abroad ('000s)	Proportion of students abroad ('expatriation rote') (%)
EC[1]	8 484.0	181.3	2.1
EFTA[1]	863.0	34.2	4.0
Former USSR and C&EE[1]	8 314.0	33.4	0.4
USA	13 975.5	24.9	0.2
Canada	1 359.0	21.0	1 5
Latin America	7 113.0	81.3	1.1
North Africa	1 486.0	101.9	6.9
Middle and Near East[1]	2 641.5	183.1	6.9
Sub-Saharan Africa	691.0	99.2	14.4
Japan	2 683.0	40.0	1.5
NICs[1]	1 989.0	106.0	5.3
China	2 147.0	95.0	4.4
India	4 806.0	33.6	0.7
Other countries of Asia and Oceania	4 998.0	70.2	1.4
Non-specified[2]		63.0	
Total	61 550.0	1 168.0	1.9

1. See Table 1 for definitions.
2. Students in a foreign country whose nationality is not known.

Note: Statistics regarding the internationol mobility of students are published by UNESCO, and are based on data from the Member States. Since the definitions and methods of data collection may vary from one country to another, one should consider the figures presented here as indicative rather than being statistically valid.

Source: OST, from UNESCO data (OST, 1993).

In terms of the ratio of foreign students to the total number of students in each country, Belgium and Switzerland are the most open countries, followed by Austria and France. The low ratios of Japan, but also of the former USSR and Italy are noticeable.

A WORLD OF STRIKING CONTRASTS AND NEW CHALLENGES

It should once again be emphasized that while the geographical distribution of science and technology reveals a highly inegalitarian world when using global indicators, the latter are not totally satisfactory. They cast little light on poorly disseminated, 'local' S&T production, and fail to do justice to achievements which in certain countries are first class. Thus, the S&T potential of countries such as India, China or Brazil, while incomparable in quantitative terms to that of the Triad countries, is no less important. China underwent a period of remarkable S&T development during the 1980s, and now has leading-edge know-how in nuclear power and aerospace technology. This is equally true of India, which has built up a national system of S&T based on a network of large-scale national research institutes, as well as developing high-quality university research. Brazil made first rate efforts during the 1960s and 1970s, but inflation and the weight of the country's international debt have compromised achievements which, in certain areas, were of international standard. Finally, without pretending to be exhaustive, it should be noted that several Arab countries in North Africa (Algeria,

TABLE 11
THE 12 COUNTRIES RECEIVING THE MOST FOREIGN STUDENTS, 1990

	Foreign students in the country ('000s)	Proportion of internationally mobile students (%)	Proportion of foreign to total students in the country (%)
United States	408	34.9	2.9
France	136	11.6	8.0
Germany[1]	92	7.9	5.3
UK[2]	71	6.1	6.0
Former USSR	67	5.7	1.3
Canada	35	3.0	2.6
Belgium[2]	33	2.9	12.3
Australia	29	2.5	6.0
Japan[2]	24	2.0	0.9
Switzerland	23	1.9	16.5
Italy	21	1.8	1.5
Austria	18	1.6	9.0
Total, 12 leading countries	957	81.9	
World total	1 168	100.0	1.9

1. 1988.
2. 1989.

Source. OST, from UNESCO data (OST, 1993).

Morocco, Tunisia) and the Near East (Egypt, Syria) have been able to set up and develop research institutes which are fully integrated into the networks of the international scientific community.

This being said, it must be pointed out that the situation for African countries, almost all the Latin American countries, certain countries in the Middle East and a large part of Asia, is very worrying. Since these countries produce only a fraction of scientific knowledge and technological know-how, they have only limited access to the global S&T potential.

The development of S&T has been largely dominated for a number of decades by considerations of economic and political power, even though the aim to widen the scope of knowledge has remained a basic motive of scientific research. Almost every national S&T system has been based on and mobilized by these considerations. Certain countries, however, are starting to question the pre-existing balances within national policies for research and technology. Many areas of S&T are linked to a 'social demand', that is, to social concerns and policies, such as public health, the evolution and conservation of the environment, communication within society, forecasting changes in the climate and their long-term impact, to name but a few.

The social issues which correspond to a crucial social demand often require a proper scientific approach, capable of providing bases for diagnosis, highlighting possible solutions, and helping decision makers develop strategies. National S&T systems are going to have to recognize new priorities, and to obtain the financial and structural resources which will enable research to be more pertinent to social issues. This will also mean that the humanities and social sciences must have enhanced status in research policies. The value of the issues they address must be recognized for its own sake, enabling the launching of research programmes linking the social and natural sciences.

The problem of providing an answer to social demand is particularly acute in Third World countries. Given the conditions in which they find themselves, it will be difficult for any kind of S&T take-off to occur for a number of decades. Their priority is to support scientific and technical research which helps in laying the foundations for social and economic development, in solving the basic problems facing their populations (such as health and food), but also in training managers and technicians capable of disseminating throughout the social body the basic techniques and scientific methods which are essential to any modern society.

One of the challenges for S&T systems in developed countries is to find the most appropriate means of contributing, via cooperation policies, to the scientific and technical take-off of their partners in the Southern hemisphere.

The national R&D systems of the industrialized countries need to re-orient their technology policies to take into account the disarmament agreements on strategic weapons signed by the USA and the former USSR (in particular the START agreements signed in 1991 and 1993). Such agreements will lead to a marked slow-down in the arms race. This has already shown up in the stoppage of growth in military research budgets in the industrialized countries, some of which have even started to decline, in particular in the USA. The debate has already been running for a number of years on the impact of military R&D expenditure on the technological competitiveness of industry, notably within the Triad. This debate can only lead to policy reviews which on occasion may be hard-hitting, and will constitute a major issue for many countries.

The 1990s will undoubtedly see the beginnings of profound changes in national research and technology systems, for the issues that have to be addressed require not only re-examination of policies, hut fundamental structural modifications.

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3 PARTNERSHIP IN SCIENCE

INTERGOVERNMENTAL COOPERATION

Michel Batisse

Scientific knowledge in any discipline is the sum total of innumerable contributions, large and small, coming from many researchers over time. The exchange of ideas and information between scientists has always been the major driving force of scientific progress, which is intrinsically of a cumulative nature. Great thinkers from countries of the Mediterranean and the Middle East were already gathering together in such places as Alexandria in the Hellenistic period, or Baghdad at the height of Arab culture. With the flowering of modern scientific thought in western Europe in the 17th century, an intense exchange of views and experiences began to take place among the most illustrious minds from different nations. A striking example of this practice is provided by Father Mersenne, in Paris, who acted for over 20 years as a link, through correspondence and visits, between such people as Boyle, Descartes, Galileo, Huygens, Pascal and Torricelli. A similar spirit animated Oldenburg in England and led to the creation of the Royal Society in 1660. In those days, the international exchange of information took place only between individual scientists. This pattern assumed larger proportions during the 18th century, with the rapid development of science and its clear separation from philosophy, but remained basically similar and indeed continues today through a proliferation of congresses, symposia and personal contacts.

SCIENCE AND GOVERNMENTS

With the increasing significance of certain aspects of science for industrial or military purposes, the interest of governments – which had hitherto been limited to such topics as the knowledge of time or methods of navigation – was soon to expand. The 19th century with the industrial revolution, and even more the 20th century with the formidable development of nuclear physics, informatics, molecular biology and other new fields, have witnessed the massive application of science to all aspects of human life through an infinite variety of technological tools and processes. The ever increasing intermeshing of science and technology, which has become the source of economic and political power, has considerably affected the tradition of the free flow of scientific information. Patenting or classifying, inspired directly or indirectly by national interests, inhibits the open exchange of knowledge in many domains and, more often than academic circles like to admit, many scientists in the developed world have become prisoners of some kind of industrial or military restriction on their freedom to communicate, thus eroding to a greater or lesser extent traditional scientific ethics (Batisse, 1973).

This situation has to be kept in mind whenever international scientific cooperation is considered. At the same time, however, such cooperation, and the sharing of knowledge which goes with it, remains essential for progress in most disciplines, and governments themselves could not but recognize this need. The first official links between two countries to achieve a common scientific objective were perhaps those established between England and France at the end of the 18th century for geodesic measurements. At a broader international level, the first true scientific cooperation project was initiated in 1824, when European astronomers agreed to prepare an International Map of the Heavens. The organization of large congresses in the principal disciplines began after 1860, and in 1875 the first permanent intergovernmental organization serving scientific purposes, the International Bureau of Weights and Measures, was established near Paris. At the same time, cooperation in all the basic disciplines was to develop on a firm basis and in a more organized fashion with the progressive creation of 'international unions'. The establishment in 1919, just after the First World War, of a council, which was to become the International Council of Scientific Unions (ICSU), provided a common frame and direction to these unions and a mechanism for contact between the national academies of science which were being set up in an increasing number of countries (Baker, 1982*a*).

Governments have not figured prominently in this process, and as a result ICSU as well as its scientific unions are considered non-governmental organizations. In reality, this complex and well developed international structure would perhaps be better described as semigovernmental. Some unions, such as those in geophysics or geology, are based upon and around the existence of strong national public services. National academies are not independent of the governments that finance them. In fact, the distinction between what is governmental and what is not governmental in the scientific field is fairly clear in some countries with a long liberal tradition, but has little meaning in most countries, particularly in the developing world. As indicated earlier, the association of science with government is in any case in direct relation to the former's role as the prime source of technology. At the same time, however, it should be stressed that the scientific unions defend the basic tenets of scientific ethics and attempt to maintain as far as possible the tradition of free exchange and free circulation of scientists with minimal political interference.

INTERNATIONAL PROGRAMMES

The objective of international cooperation is not only the exchange of existing information. It often has a more ambitious purpose, that of acquiring new knowledge, through a common programme of research where the different partners agree to pool their intellectual, financial and logistic resources. This is what Gauss already had in mind when he launched the first coordinated effort to study the magnetism of the Earth. Such a cooperative research approach was later exemplified by the organization, in 1882, of the International Polar Year when 11 countries agreed to conduct simultaneous studies of Arctic phenomena through a set of observing stations, and to see their efforts coordinated through an international commission (Baker, 1982*b*). A Second International Polar Year was launched 50 years later. Although the exploitation of its results was hampered by the Second World War, it witnessed the participation of 44 countries. Quite obviously, such large-scale operations in these difficult regions could only be conducted with the active support of the governments involved. This fact became even clearer with the organization, in 1957-58, of a third polar year which took the more appropriate name of the International Geophysical Year (IGY) and whose activities were conducted under the leadership of ICSU.

By the magnitude of the undertaking, which saw such considerable events as a thorough exploration of the Antarctic, the launching of the first satellite, or the discovery of the Van Allen belts, IGY gave an entirely new dimension to international scientific cooperation. Its success led to the decision to continue many of its operations and, as a follow-up, to launch several similar types of projects, such as the International Year of the 'Quiet Sun' (1964-65) for solar research, or the Upper Mantle Project (1962-70) and the International Geodynamics Project (1970-80) for the solid Earth. At the same time, cooperative research on the atmosphere, which had known an early start in view of the practical importance of weather information and which had led to the creation in 1873 of an International Meteorological Organization, was considerably enhanced by IGY. From 1967 to 1970, for instance, a Global Atmospheric Research Programme was conducted jointly by ICSU and this intergovernmental institution, which had been renamed the World Meteorological Organization (WMO). With the growing concern about possible changes in climate through the greenhouse effect, such major cooperative activities relating to the atmosphere were bound to expand within such frameworks as the World Climate Research Programme initiated in 1980, or under other associated undertakings (Davies, 1990).

It is important to note that the research programmes which have just been mentioned all deal with certain aspects of the physics of the Earth and that although WMO, which brings together all national meteorological services, has been increasingly involved, these programmes have often been considered, somewhat mistakenly, as being of a non-governmental character because they were largely based on the work of the international unions. In fact, only a limited number of countries could take part with sufficient human and financial resources in these coordinated geophysical studies, which did not entail ground field work in all parts of the world. In other words, most developing countries were more spectators than actors in these great ventures. The success of IGY was such, however, that other groups of scientists were encouraged, and suggested that worldwide research programmes devoted to their own disciplines would provide considerable results and much needed information. This was the case with biologists, who were particularly concerned with the mounting environmental problems arising all over the world from the parallel increases in human numbers and the consumption of natural resources. It soon resulted in the organization, under the auspices of ICSU, of an International Biological Programme (IBP), which was operational from 1966 to 1972 and produced a considerable amount of new knowledge, contributing significantly to modern ecological thought. Biology, however, operates in ways very different from geophysics. Therefore, despite its unquestionable scientific success, IBP suffered from at least one major shortcoming, which its dynamic scientific director, Barton Worthington, clearly expressed when noting that under IBP: 'it proved impossible to get full participation from the developing countries, which stood the greatest chance of benefiting from ecological research' (Worthington, 1983). This situation resulted not only from the scarcity of scientific means in these countries but from the fact that most science in the Third World is undertaken by governments and that governments want nowadays to be involved when field work is conducted on their own territory. Very soon, in fact as early as 1966, some people understood the need to provide 'a follow-up and adequate extension' of IBP through the direct involvement of an intergovernmental agency, and this led to the organization by UNESCO, in 1968, of the Conference on the Rational Use and Conservation of the Resources of the Biosphere, where the foundation stone of the Man and the Biosphere Programme (MAB) was laid (Bourlière and Batisse, 1978).

UNESCO ENTERS THE SCENE

This was of course not the first significant effort from UNESCO in promoting international scientific cooperation. Although in the early discussions among ministers of education which took place in London during the Second World War it had not been foreseen that science would be included in the mandate of the new organization, the importance of scientific discoveries in public affairs, particularly after Hiroshima, and the need to restore channels of scientific communication between countries, prompted the introduction of the 'S' in UNESCO. Symbolically, the first Director-General chosen to lead the Organization was a well-known biologist, Sir Julian Huxley. From the beginning, UNESCO devoted itself to two major concerns in science: to support and maintain close contacts with the international scientific community, in particular with ICSU and its unions, and to facilitate the participation of developing countries in the advancement of knowledge, particularly with the establishment of several 'science liaison offices' in Asia, the Middle East and Latin America. To these two objectives another one was soon to be added, although not in an explicit way, namely to mobilize the efforts of scientists worldwide towards exploring possible solutions to certain important problems, bearing in mind that an intergovernmental organization is meant to pay attention to those issues which confront its Member Countries.

A first step in this direction was the creation in 1948, jointly with the French Government, of the International Union for the Conservation of Nature (IUCN), now IUCN–The World Conservation Union. At about the same time, following a proposal from India, UNESCO was asked to explore the possibility of setting up an International Institute of the Arid Zone, dealing essentially with those regions of the world which receive too little rainfall. This decision was to have major consequences for the development of the scientific work of the Organization. The expert panel convened to study the feasibility of the suggested institute concluded, very wisely indeed, that a single centre would necessarily be remote from most arid regions and very cumbersome to administer. They advocated instead the establishment of an international advisory committee, which held its first session in Algiers in 1951, thus initiating the Arid Zone Programme. Its last session took place in Jodhpur in 1964, at the end of what had become a 'major project' of the Organization. As an outcome of this long effort, a collection of some 30 state-of-knowledge volumes were published, interdisciplinary studies were conducted in a number of local areas, hundreds of specialists were trained, several national research centres were created, and above all, a worldwide network of contacts was established. This Programme had a profound influence on the evolution of UNESCO's approach to international scientific cooperation. The following lessons, in particular, could be drawn from this 15-year experience:

An international programme including very different types of action in research, information exchange, technical assistance, training, etc. can be guided by a simple advisory committee consisting of well-chosen individuals.

All countries concerned, whether developed or developing, show considerable interest in mobilizing scientific resources from the entire world to contribute towards solving a common practical problem of global or large-scale regional dimensions.

An intergovernmental organization is well suited to promote scientific cooperation programmes focusing on socio-economic issues, requiring a multidisciplinary approach, and calling upon both basic and applied research and upon both natural and social sciences.

Beyond a certain level, such a programme calls for clearer commitment and more formal support from governments in order to have decisive and lasting effects at the country level.

INTERGOVERNMENTAL PROGRAMMES WITH A GEOGRAPHICAL DIMENSION

It should be noted here that in the early 1960s, the emergence of many newly independent countries led to a massive demand for development. The modest technical assistance activities conducted previously by the UN agencies suddenly appeared very insufficient, although they were augmented by the creation of the United Nations Development Programme (UNDP). This also led to a reassessment of the relationships between science, technology and development, with a growing demand from Third World countries to participate in international ventures and to be provided with some basic means of doing so. Putting together this pressure from the developing countries with the emergence of rapid travel and communication facilities, and the perceived success of such efforts as the IGY and the Arid Zone Programme, one can easily understand the dramatic increase in scientific cooperation which characterized this period.

The field of oceanography calls for large logistic facilities, including research vessels and long-distance communications, and had thus far been practised jealously by only a handful of nations, while other countries were increasingly concerned about the possible exploitation of their marine resources. UNESCO, which had already been promoting research in the field, became the natural body to coordinate expanded activities. The first major objective was to organize the International Indian Ocean Expedition (1959-65) and in which 40 ships from 13 countries participated (Behrman, 1981). The method chosen was to set up an Intergovernmental Oceanographic Commission (IOC) within the framework of UNESCO, where all countries could be represented and where cooperation among governments and with the scientific community could be smoothly articulated. The success of the expedition gave a lasting impetus to IOC, which has since developed a number of regional and global programmes concerning various aspects of ocean research as well as technical support to developing countries, thus providing the marine sciences with the kind of intergovernmental cooperative framework which WMO provides for the atmosphere.

On the other hand, while the Arid Zone Programme had shown the key role of fresh water in the development of the regions concerned, it had become clear that all parts of the world were in fact facing growing water problems. Quite naturally therefore, this earlier medium-scale programme was to be followed by a major worldwide cooperative study on water: the International Hydrological Decade (IHD) (1965-74). This was a concerted effort, with a fixed time-frame, to understand and analyse the planet's water cycle, to evaluate surface- and ground-water resources, to establish the basis for their rational management (both as regards quantity and quality), to train the necessary specialists, and to reinforce the status of hydrology in all countries. The ambition was comparable to that of IGY or IOC. The method, however, was different. The coordinating mechanism was a council, with only a limited number of participating countries elected on a rotating basis by the General Conference of UNESCO, represented essentially by experts and providing guidance to a common programme of research and monitoring designed by consensus. This council thus constituted an intergovernmental steering body which was lighter than a fully fledged commission like IOC, but more representative of world diversity than a simple scientific committee. Although all countries were not part of the council, they all participated in the programme through specially established national committees in which the various agencies and institutions dealing with water in each country were represented, and which were served by the IHD secretariat (UNESCO, 1991).

This coordinating mechanism proved to be sufficiently autonomous and flexible to ensure the success of the IHD. Through this process, it was considered that more permanent cooperation in the field of hydrology was desirable, so that at the end of the decade, while it appeared that WMO would not be in a position to take over the whole subject, it was decided to continue activities within UNESCO's framework along similar lines, with successive phases being reviewed every four years. This led to the International Hydrological Programme (IHP), which is still in operation today, with national committees operating in 140 countries.

In the same way, it was felt appropriate to explore whether the same formula could be applied to other global subjects where a need for intergovernmental cooperation seemed to have arisen, for instance in ecology, in geology or in seismology. The Man and the Biosphere Programme (MAB), the origin of which was outlined earlier, was the first test of this organizational structure, using the same model of an intergovernmental coordinating council (where 30 elected countries together with other governmental and non-governmental organizations are represented), a similar network of national committees, and a central secretariat in UNESCO. Although the subject matter under MAB is far more diversified and less clearly focused than in hydrology, since it deals with the entire gamut of interactions between human activities and the various natural or man-modified ecosystems of the planet, and since it should by essence follow an interdisciplinary and problem-oriented approach, this organizational structure proved by and large to be appropriate. It is still in operation today after more than 20 years, with national committees in some 110 countries and a worldwide network of over 300 Biosphere Reserves located in 80 countries (Batisse, 1980).

Before the IHD, hydrology had been a somewhat neglected discipline and, before MAB, what can be called applied ecology in a broad sense was not an organized domain, nationally and internationally, even though IBP had opened the way on a more fundamental level. But geology offered a very different picture, with well-established geological surveys and agencies in most countries and a new but strong international union. When the idea emerged of harmonizing our global picture of the history of the Earth through an International Geological Correlation Programme (IGCP), it was felt therefore that the IHD or MAB formula would not be appropriate. What appeared to be needed was a combination of the already solid cooperation between scientists and services within the International Union of Geological Sciences (IUGS) on the one hand, and intergovernmental support provided by UNESCO, in which developing countries could play an active role, on the other. The result was the setting up of a board of experts appointed jointly by UNESCO and IUGS to lead the programme, with technical assistance from a scientific committee. This approach, which is also still in operation, has given a large degree of satisfaction for a programme which keeps a highly technical character. A similar approach was explored for seismology but did not prove appropriate, partly since intergovernmental action in this field was taking place more at the regional rather than at the global level. This, however, might gradually evolve with the increasing linkage between regional seismological observatory networks.

It is abundantly clear from the preceding historical account that truly intergovernmental worldwide scientific cooperation – whether it is conducted at the so-called non-governmental level or with an intergovernmental organization – is particularly appropriate, and therefore relatively easy to promote, when dealing with disciplines which have a 'geographical' dimension. It is then equally clear that there is a limit to the number of domains in which this applies. It is therefore not surprising that, since the launching of IGCP in 1973, there has been a break in the emergence of such new programmes. By then, the oceans, fresh water, earth sciences, and terrestrial ecosystems were well covered with a major involvement from UNESCO, while the atmosphere, climate and some aspects of hydrology were covered by WMO. New tools such as satellites, and new concerns such as global environmental change, were simply adding new dimensions to more or less already existing mechanisms. The International Geosphere-Biosphere Programme, now being promoted under ICSU leadership, represents the latest development in this continuum of large-scale comparative research activities relating to our planet, and in which governments are bound to have a large role to play.

INTERNATIONAL CENTRES AND PROGRAMMES

When it comes to scientific cooperation in 'non-geographical' subjects, where national sovereignty or government services are not directly involved, UNESCO has usually been led to adopt a purely non-governmental approach, as for instance in the case of brain research or cell research, when it facilitated the creation of the International Brain Research Organization (IBRO) in 1950, the International Cell Research Organization (ICRO) in 1962, or the World Federation for Culture Collections (WFCC) in 1970, which were meant to be very light and flexible mechanisms run by the scientists concerned. In fact, IBRO became associated with ICSU in 1976, as did ICRO in 1985, and WFCC became part of the International Union of Microbiological Societies. Similarly, it was essentially through non-governmental channels that programmes in the renewable sources of energy, or in microbiology and biotechnology were developed by UNESCO. But conversely, a strictly intergovernmental approach has been followed, with varying degrees of success, in certain domains where territorial considerations are not involved, such as physics or informatics. The first and outstanding example is the European Centre for Nuclear Research (CERN), which was created as early as 1954 through the decisive catalytic action of UNESCO, a fact which has been completely overshadowed by the very fame of this large-scale facility which has today reached the rank of world leader in the field. Success here is directly linked to two specific factors: the common will of a regional group of industrialized countries having comparable interests and talent in a new field (nuclear physics); and the fact that none of these governments could easily meet the cost of building and operating a giant accelerator. Could such a success be repeated? This was attempted in the emerging and burgeoning field of informatics, with the creation in 1961, after a long period of uncertainty, of the Rome International Computation Centre. The ambition here was to provide all countries with opportunities for an open exchange of knowledge and access to large computing facilities. But the field was in a state of very rapid evolution and linked to huge private business interests. Only a handful of countries eventually joined the Centre. The lesson from the Arid Zone Programme concerning the difficulty of setting up a viable international centre had not been sufficiently considered. The Rome Centre was later transformed into an independent International Bureau for Informatics which was subsequently dissolved in 1988. It remains true that, when countries do have strong common motivations and sufficiently homogeneous scientific capacities, intergovernmental research centres of a regional nature can be quite successful. The European Community is exploring this approach today in various scientific and technical fields.

At the global level, as an effort to facilitate the exchange of information and even more as a means of allowing developing countries to have better access to science and technology, UNESCO has attempted to promote intergovernmental cooperation in certain domains where a more structured organization of activities appeared to be required. This was considered to be the case in the vast and complex area of scientific and technical information, where the setting up of a world system was initiated in 1971 under the acronym of UNISIST. Since all disciplines needed to be covered, the effort was not limited to the scientific field and it developed into a General Information Programme (PGI). This ongoing UNESCO programme has been organized along very much the same lines as IHP or MAB, although it is of a completely different nature since it is not a concerted research effort but essentially a means of promoting and achieving cooperation. In a somewhat similar spirit, an Intergovernmental Informatics Programme was launched in 1985, focusing on regional technical information networks, on professional training and on infrastructure development at national level.

THE VALUE AND LIMITATIONS OF INTERGOVERNMENTAL PROGRAMMES

The brief outline of the evolution of intergovernmental scientific cooperation given above, and the major role which UNESCO has played in innovating new means of organizing it, show the growing importance of associating developing countries with what had so far been almost a monopoly of the industrialized world. At this stage it is worth recalling the more or less common features which characterize the intergovernmental programmes promoted by UNESCO (and in fact also by WMO and in certain cases by ICSU), thus underlining the advantages of this approach as well as some of its limitations:

- They are programmes which, by the very nature of the subject or problem to be tackled, demand international cooperation, usually at global level.
- They are programmes in which both developed and developing countries have a strong interest in participating, because they contribute to a better understanding of natural phenomena, or a better knowledge of natural resources, or a better sharing of information.
- They are concerted or coordinated programmes formulated by their international governing bodies, whose execution relies mainly on activities conducted by the participating countries, usually under the guidance of *ad hoc* national committees on which government agencies, universities and research institutions are represented.
- They are programmes which make possible the coordination of effort and transfer of knowledge through small secretariats established within UNESCO, and in which bilateral or regional cooperation can play an important role through direct contact between national committees.
- They are programmes which are not meant to be of an academic nature but rather problem-oriented, involving interdisciplinary approaches and field activities, and inviting interaction between research workers and decision makers to allow for the correct formulation of issues and practical utilization of results.
- They are programmes not limited to research and information exchange, but including a strong training component, which is essential for building up the national capabilities required for participating actively in the international effott and at the same time achieving the related national goals.
- They are programmes to be implemented with the active participation of the other UN agencies and non-governmental scientific organizations concerned, which all have statutory representation on the governing body.

It could be added that this type of intergovernmental scientific cooperation is highly decentralized to country level, through national committees, and that the funds allocated to its central and regional coordination and stimulation are considerably multiplied through the bilateral and national contributions made at implementation level. Similarly, the number of scientists involved in any such programme may be very large, when all the activities at national or local level are counted.

Conversely, the worldwide intergovernmental mechanism can present certain dangers, the main one being a certain crystallization of projects over time with the risk of routine, if reassessment of purpose is not made from time to time, and if adequate quality control of research activities is not carried out. There can also be a certain screening effect by national committees, who might tend to monopolize excessively the participation of their country. In addition, representatives from some countries on the governing body may have insufficient scientific qualifications. These dangers, real as they may be, can be overcome. Programmes of fixed-term duration should be preferred, and if they are open-ended, they should be subject to periodic critical evaluation. Countries and local scientists should be encouraged to participate fully by the governing body and the secretariat. Naturally, appropriate support should be provided to developing countries to enable their fullest possible participation. In this respect, certain intergovernmental projects may have the tendency to move at the pace of the slowest, but this is a price that has to be paid when universal participation is required.

The movement which led governments to take an active interest in scientific cooperation is not likely to weaken, as demonstrated recently by the signing, after laborious negotiations, of world conventions on such subjects as climate change and biological diversity, where many of the

BIOSPHERE RESERVES

In the past, the conservation of flora and fauna was usually implemented through large national parks or small biological reserves located in relatively pristine regions and from which human economic activity was excluded. Many such protected areas, particularly in developing countries, are threatened by encroachment by people living in the surrounding territory, looking for agricultural land and timber. On the other hand, many inhabited landscapes, which do not qualify for conventional types of protection, nevertheless maintain important elements of biological diversity, including wild relatives of cultivated crops or domesticated animals. Such areas, as well as larger zones around national parks or biological reserves, are often appropriate for the setting up of Biosphere Reserves – which constitute a relatively new, non-conventional type of protected area.

The Biosphere Reserve concept was introduced into UNESCO's Man and the Biosphere intergovernmental research programme in the early 1970s, and has been kept flexible in order to accommodate the extreme diversity of situations across the world. In essence, each Biosphere Reserve performs three basic functions:

1. A conservation function, which ensures a more systematic *in situ* protection of genetic resources and species and of the ecosystems where they occur, whether natural or semi-natural.

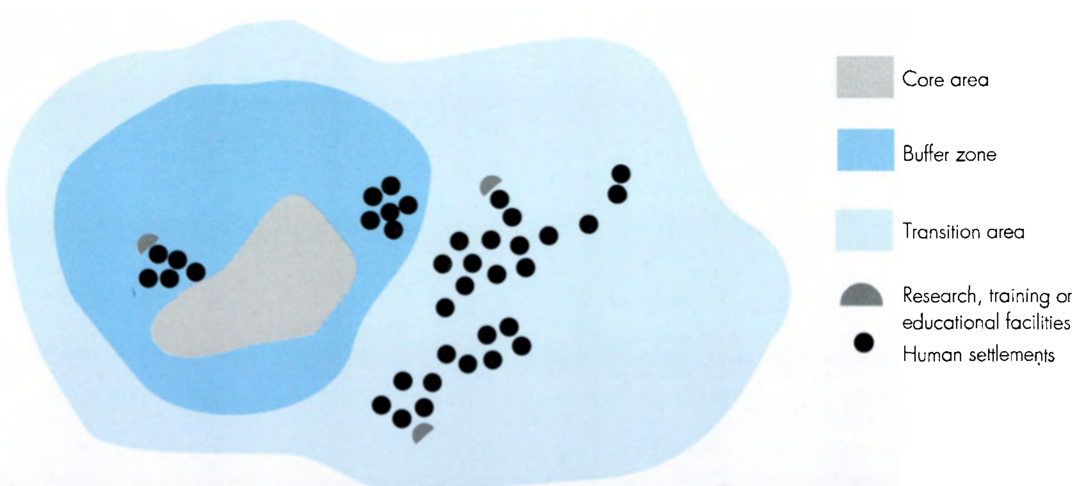
2. A development function, which promotes or maintains land-use practices allowing the local people to benefit fully and directly from the management of the Biosphere Reserve.

3. A logistic function, which provides research, monitoring and training facilities and ensures linkages within an international network of Biosphere Reserves.

Performing these three functions together in a satisfactory way naturally constitutes a considerable challenge which can only be met progressively through suitable management mechanisms. This relies in particular on an innovative and widely adopted zoning system including one (or several) minimally distributed *core area* that protects an important terrestrial or coastal ecosystem or landscape, surrounded by a well delineated *buffer zone* devoted to a number of activities including, as the case may be, traditional land use, recreation and tourism, land rehabilitation, environmental education and research, etc. which are compatible with the conservation objectives of the core area. Finally, in an outer *transition area*, efforts are made, in cooperation with the local population, to develop sustainable resource management practices.

Today, the international network serviced by UNESCO consists of 311 Biosphere Reserves located in 81 countries and covering a total area of approximately 170 million hectares. It provides a good example of intergovernmental cooperation for better protection and management of ecosystems and landscapes, for the conservation of biological diversity, for the exchange of information and personnel, and for concerted ecological research and monitoring at both regional and global levels.

BIOSPHERE RESERVE CONCEPT



decisions to be taken will depend on scientific assessments of the situation, difficult and uncertain as it may be. The demand from developing countries for a fair share of access to scientific knowledge is bound to increase, since it forms the basis upon which the much desired transfer of technology can take place. In this context the traditional integrity of science and the free flow of information and scientists have to be maintained at all costs. UNESCO and ICSU have to see to it that this is always kept in mind when organizing the new cooperative research ventures which will have to be developed in the future and which in most cases, whatever name they are given, will involve the direct or indirect participation of governments. From its very beginning, UNESCO, while facing the diversity of cultures, natural conditions and levels of development in the world, has been compelled to ask itself how it could reach the consensus of thought required to achieve its predominantly intellectual objectives. Experience has shown that scientific cooperation is a fruitful and relatively open field where the practical ends, which are those of the Organization, can be achieved. As early as 1947, the French philosopher Maritain advocated the identification of a 'common practical thought' as the strongest axis for the work of the Organization. After nearly 50 years of experience, it is clear that the scientific programmes of UNESCO do respond successfully to this challenge.

MICHEL BATISSE, a French engineer and physicist, has spent most of his career with UNESCO, where he developed environmental and natural resources programmes. He was the coordinator of the Major Project on Arid Lands and later the organizer of the International Hydrological Decade (IHD) and of the Man and the Biosphere Programme (MAB). He developed in particular the concept of Biosphere Reserves and retired from the Organization as Assistant Director-General (Science). He is presently President of the Mediterranean Blue Plan and a senior adviser to UNEP and UNESCO.

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THE EXAMPLE OF OCEANOGRAPHY

Ulf Lie

'Partnership' is a relatively new term in the vocabulary of international cooperation. It implies equality and two-way communication to a much higher degree than previously used terms such as 'transfer of technology' or 'technical assistance'. This change in terminology is not fortuitous. During the last decade it has become increasingly clear that the problems the world is facing in terms of environmental degradation, food shortage, population growth and warfare, affect us all. The efforts to solve the problems and thus avoid massive instability and conflict require true partnership in international cooperation.

The need for partnership is particularly strongly felt in the field of environmental sciences. The natural systems of the biosphere, hydrosphere and atmosphere are governed by the same basic processes the world over, and therefore scientific cooperation and exchange of information are of mutual benefit.

The interdependence in scientific cooperation is a strong factor in scientific capacity building worldwide. Exchange of scientific data and information require universally accepted standards of quality, which in turn are related to the level of training of personnel and the availability of instrumentation. Contributing to the enhancement of scientific capability in all countries is therefore a matter of mutual interest.

PARTNERSHIP AND INTERNATIONAL OCEANOGRAPHY

The concept of partnership in cooperative scientific studies of the ocean is natural and indeed necessary. The ocean is contiguous, its water masses and whatever they contain in terms of living things (e.g. fish) and non-living substances (e.g. pollutants) move freely across political boundaries. The effects of overexploitation of a fish stock or of polluting the marine environment in the coastal zone of one country will be felt in the coastal areas of neighbouring countries, and this is an obvious source of conflict.

With the rapid development of ocean fisheries in European waters at the beginning of the 20th century, it was recognized that international cooperation was needed to provide the necessary scientific data in support of the fisheries industry (Roll, 1983). This led to the establishment of the International Council for Exploration of the Sea (ICES) in 1902, and since 1964 the Council has been based on a formal convention. At the time of its foundation, the Member States of the Council were eight European countries, whereas today the membership counts 18 European and North American countries. Although the primary purpose of the ICES was to conduct scientific studies in support of fisheries, the Council later became the major organization for marine science studies in the North Atlantic region. Today the ICES has a very decisive role in the formulation of the fisheries policies of its Member States and in the management of shared fish stocks in the area.

The ICES was the first organization to demonstrate successful partnership among nations in studies and management of the ocean and its resources and is an example that has been followed in a number of cooperative investigations of the ocean that have had a major impact on the development of marine sciences.

THE EXAMPLE OF THE INTERNATIONAL INDIAN OCEAN EXPEDITION

The famous oceanic expeditions of the 19th and the first half of the 20th century were for the most part national expeditions (Roll, 1983), but after the Second World War it became evident that a synoptic view of the dynamic variables of the oceans, such as current structures and stratification, could not be obtained through a single-ship operation. For the successful study of these phenomena there was a need for cooperative investigations with several ships and teams of scientists working together.

The most famous example of a cooperative study of the ocean was the International Indian Ocean Expedition (IIOE), which lasted from 1959 to 1965. The initiative for the expedition was taken by the Scientific Committee on Oceanic Research (SCOR) of the International Council of Scientific Unions (ICSU). Of the major ocean basins in the world, the Indian Ocean and its physical, chemical, biological and geological features, like the polar seas, was little known, and comprehensive studies of this ocean required the joint efforts of the international community of oceanographers.

The IIOE was conceived, planned and in large part executed by the major oceanographic institutions in the world, and was dominated by the industrial countries. However, of the 40 ships participating, there were vessels from India, Pakistan, Thailand and Indonesia, and a further six countries from the region participated in the studies (Behrman, 1981). The concept of partnership in oceanographic investigations was thereby broadened to include the developing countries, and was demonstrated by activities in the biological components of the IIOE.

It was clear from the outset that shipment of the large collection of biological material, particularly zooplankton, to scientific institutions around the world for sorting and identification would be a cumbersome and ineffective operation. The suggestion was therefore made that a biological sorting centre be established in the region, where local scientists and technicians in cooperation with leading planktologists of the world would sort, identify and count the contents of the biological samples of the IIOE. The Indian Ocean Biological Centre was established in Kerala, India, in 1963, and the Centre has since become a division of the National Institute of Oceanography at Goa. The Indian Ocean Biological Centre, as well as the Indian National Committee on Oceanographic Research which was established to coordinate the Indian programme of the IIOE (Qasim, 1982), were important nuclei in the development of India as a major power in oceanographic research. Similarly, marine science development in countries of the region like Pakistan, Thailand and Indonesia was to a considerable degree stimulated by the scientific partnership facilitated by the IIOE.

THE INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

The IIOE also had a major impact on institutional arrangements for international marine science. During the planning phase of the IIOE it soon became clear that large-scale oceanographic expeditions required the participation of governments, and that SCOR, a non-governmental organization, was not well suited for the management of the programme. On the recommendation of the international marine science community engaged in the planning and execution of the IIOE, UNESCO established the Intergovernmental Oceanographic Commission (IOC) at the 11th Session of its General Conference in 1960 for the purpose of: 'learning more about the nature and resources of the oceans through concerted actions of its Member States' (IOC Statutes, Article 1).

IOC, which was given responsibility for the management of the IIOE from 1961, had at the start a membership of 40 nations, mostly industrial states, but today the membership is 123 and dominated numerically by developing countries.

Based on the example of the IIOE, a series of cooperative investigations of important ocean areas, e.g. the Tropical Atlantic Ocean (1963-64), the Kuroshio and Adjacent Regions (1965-77) in the western Pacific Ocean, and the Caribbean and Adjacent Regions (1967-76), were carried out under the coordination of the IOC. These investigations greatly stimulated the development of marine sciences in the world, and led to the formation of the existing sub-commissions of the IOC, the IOCARIBE and WESTPAC.

PARTNERSHIP IN COOPERATION UNDER INTERNATIONAL CONVENTIONS

International cooperation under conventions regulating the marine environment is of a much more recent date than scientific cooperation, simply because marine pollution was not a serious problem until the 1950s. The first international agreement to regulate marine pollution was the International Convention for the Prevention of Pollution of the Sea by Oil of 1952, with amendments in 1962 and 1969. The aim of this Convention was to prevent sea pollution by the discharge of oil from ships and it was followed by global conventions, such as the London Dumping Convention (Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter) of 1972, and regional conventions such as the Oslo Convention of 1972 on dumping of harmful substances from ships and aircraft, and the Paris Convention of 1974 on prevention of marine pollution from land-based sources. Today there are many global and regional conventions for the protection of the marine environment and regulation of the exploitation of marine resources, which have had a major influence on the state of the marine environment and its resources.

THE UNITED NATIONS CONVENTION ON THE LAW OF THE SEA

The long history of partnership among nations in scientific studies of the ocean and in international cooperation for the protection of the ocean environment and rational use of its resources, was crowned by the Third United Nations Conference on the Law of the Sea. The Conference lasted from 1973 to 1982, and the lengthy negotiations were probably as important as the resulting convention for the development of marine sciences in the world (Lie, 1990). The ocean environment and its resources were at the forefront of the international political agenda and in the media, all major international organizations with responsibilities in ocean affairs took part, and a large number of developing countries became aware of the need to develop national marine science capabilities.

The Convention on the Law of the Sea (UNCLOS), which was signed in 1982, is an attempt to establish a comprehensive regulation of international ocean affairs. Nearly one-third of the Convention's 320 paragraphs refer to marine science, and there are strong recommendations for scientific cooperation. Thus, Article 244 states, *inter alia*:

'... States, both individually and in cooperation with other states or with competent international organizations, shall actively promote the flow of scientific data and information and the transfer of knowledge resulting from marine scientific research, especially to developing states, as well as the strengthening of the autonomous marine scientific research capabilities of developing states through, *inter alia*, programmes to provide adequate education and training of their technical and scientific personnel.'

Such was the plea enunciated by the UNCLOS for partnership in strengthening the marine science capabilities of developing states.

One of the most far-reaching parts of the UNCLOS is the establishment of the Exclusive Economic Zone, i.e. that the coastal or island state has full jurisdiction in the ocean area within 200 nautical miles from the coastline. Many small states have thereby had a manifold increase in the area under their national jurisdiction, and have thus gained access to the available marine resources. For many coastal developing states this has in fact constituted the greatest transfer of natural resources in history (Lindén, 1990), a fact which has gone largely unnoticed.

The coastal state has the right (Article 246): '...to regulate, authorize and conduct marine scientific research in the exclusive economic zone and on their continental shelf...' and thus to grant or withhold consent for research by other states or international organizations. The decision by the coastal state whether to grant consent or not requires national ability to evaluate proposed research projects, i.e. a minimum cadre of trained scientific personnel must be available in each coastal state. Therefore, there was a need for a major expansion of the facilities for training and education.

PARTNERSHIP AND THE IOC WORKING COMMITTEE FOR TEMA

The experience with the International Indian Ocean Expedition demonstrated that truly international or global investigations depend upon the active participation of all states with marine interests. However, it was equally clear that the vast disparities in the level of ocean science development were a major impediment to further progress, and there was a need for technical assistance and transfer of technology in order to establish the level of equality needed for partnership in science. To emphasize the importance of capacity building, IOC established in 1972 its Working Committee for Training Education and Mutual Assistance (TEMA). The most important task of TEMA as described in paragraph iii of the Terms of Reference was:

'...transfer of technology and technical assistance to developing Member States in marine science aspects of ocean affairs, in order to build up their national capabilities to participate fully in ocean research of interest to them, including IOC programmes, and to achieve self-reliance in marine sciences as a whole; ...'

Thus it was clear from the beginning that the aim of TEMA was two-fold: to enable Member States to participate fully in ocean research, as well as to achieve self-reliance in marine sciences.

During the 1970s the TEMA programme was put at the forefront of IOC's activities: regional TEMA meetings were held in several regions of the world in order to discuss needs and seek solutions with developing Member States; fellowship programmes and other training programmes were developed and executed; and attempts were made to establish a permanent funding system for TEMA matters: the TEMA Voluntary Cooperation Programme.

Since the establishment of the TEMA Committee, IOC has actively developed training and mutual assistance programmes, but in retrospect it seems that expectations outpaced the rate of programme development. One reason was that the establishment of TEMA coincided, unfortunately, with the beginning of a global recession, and funds for TEMA activities became more limited, but the most important reason was the rapid change in the awareness of the importance of the ocean, stimulated by the Third United Nations Conference on the Law of the Sea. The new awareness resulted in a rapid increase in the membership of the IOC, and in increased demands for TEMA programmes.

To meet the need for training and education programmes, IOC developed the UNESCO-IOC Comprehensive Plan for a Major Assistance Programme to Enhance the Marine Science Capability of Developing Countries. The aim of the Plan is to assist states:

'...to achieve their national goals in marine affairs, as well as to contribute to overall national management and protection of the oceans through concerted actions in regional or global scientific programmes ...'

The Comprehensive Plan, which is a strategic plan with a time-frame of 20 years, was adopted by the 12th Session of the IOC Assembly in 1982. The Plan has guided the TEMA related activities of the Commission since its adoption, and IOC has developed concrete action plans on the basis of the Comprehensive Plan.

In spite of the impressive efforts made by states and international organizations in marine science capacity building, the gap in science and technology capability between the developed and developing nations has in fact widened during recent decades (Lie, 1992). From 1970 to 1983 the number of marine scientists in industrial countries increased from 4 900 to 14 400 (294%), while the increase in developing countries was from 800 to 3 600 (450%). Although the growth rate in developing countries is impressive indeed, the fact remains that the number of new scientists added to the marine science communities of industrial countries was more than three times greater than in developing countries. Furthermore, during recent decades there has been a very rapid development in sophisticated marine science instrumentation, to which scientists in developing countries have limited access. In order to attain the full benefit of partnership in marine sciences it is therefore necessary to make a substantially increased effort for capacity building in developing countries.

PARTNERSHIP AND THE FUTURE

The major issues facing humanity in the near future are possible global warming caused by emission of greenhouse gases to the atmosphere, and the spectre of major global food shortages caused by population growth and dwindling natural resources. In order to cope with the problems and to design the necessary political solutions, the world community of nations is in need of the best available advice from scientists. Such advice must be obtained in a general and global, as well as in a specific regional setting, and this requires international cooperation guided by the concept of partnership.

The marine sciences have an important role to play in global climate change studies, partly because the ocean systems to a considerable degree control the development of atmospheric processes, and partly because possible effects of global warning, such as sea-level rise, may have significant socio-economic consequences for the entire world community of nations. Therefore, the Member States of international organizations, including the Intergovernmental Oceanographic Commission, are actively engaged in organizing scientific studies and evaluating climate change consequences. IOC, as co-sponsor of the World Climate Research Programme with WMO and ICSU, is taking part in a major scientific research project, the World Ocean Circulation Experiment (WOCE) which aims to measure and understand large-scale circulation and the controlling factors of the water masses of the ocean, and their relationship to the global climate system.

Furthermore, IOC in cooperation with WMO and UNEP has taken steps to establish a Global Ocean Observing System (GOOS), which will monitor the state of the ocean environment and provide data for management decisions regarding the ocean and its resources.

Linked to the question of climatic change is the question of future ability to satisfy the global energy demand. Assuming a drastic reduction in the world production of oil and gas, it is conceivable that many countries will have to resort to the utilization of other fossil fuels, such as coal or oil shale. Such a change in energy sources will probably further enhance the greenhouse effect, and accelerate its adverse consequences. In that context, every effort should be made to investigate the possibility of harnessing the enormous energy potential of the oceans. This includes wave and tide energy, and particularly the energy to be drawn from the vertical temperature gradient in the ocean (Ocean Thermal Energy Conversion).

The role of the ocean in global food production is another important subject for international cooperation guided by the concept of partnership. The Food and Agriculture Organization (FAO) estimated that, if equitably distributed, the world production of food in 1985 would satisfy the requirements of a world population of 6 billion, i.e. approximately today's world population. There are different prognoses for the year of attaining a stable world population. The most probable scenario according to United Nations estimates is a world population of 10 billion in 2050, eventually reaching stability at about 11.6 billion. Thus, one must conclude that the world's food production will have to be about double the 1985 level in 50-60 years' time, in order to maintain the present ratio of food production to population size. It is highly unlikely that this goal can be reached with conventional agriculture alone, and every effort must therefore be made to increase the harvest from the ocean.

Food production from the ocean contributes at present only 5-10% of the total world consumption. Gulland (1970) estimated the maximum annual sustainable yield of the commercial fish populations of the world as being about 100 million tonnes, and recent fisheries statistics show that the catch level is now relatively stable at about 90 million tonnes per year. Marine aquaculture (mariculture) is growing, but the growth rate falls very much short of the need in view of a doubling of the world population during the next century. We must therefore mobilize our global scientific capacity towards innovative approaches to the question of ocean productivity in order to increase the ocean's capacity for food production.

ULF LIE is Professor of Environmental Sciences and Director of the Centre for Studies of Environment and Resources at the University of Bergen, Norway. A marine ecologist with many publications on zoobenthos, zooplankton and fish ecology to his name, Dr Lie was oceanographer and Research Associate Professor at the University of Washington, Seattle, USA, between 1962 and 1970 before returning to Bergen. From 1987 to 1991 he served as Chairman of the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

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COOPERATION FOR DEVELOPMENT

Abdus Salam

My credentials for contributing to this *World Science Report* are my involvement in the creation and in the direction of scientific institutions serving the needs of the developing countries over the last 30 years. I have always been convinced that science is a heritage of mankind and that, though the great developments of science have taken place in Europe and in the New World in these last centuries, there are no reasons why the poorer countries of the world should not contribute to its progress nor benefit from its fruits. In my undertakings, I have realized the importance of the values of partnership and of solidarity at all stages of my endeavours. Men of great talent – scientists, administrators, international servants, government officials and heads of state – have helped me in setting up several institutions in Trieste, the Italian city where I live most of the time, and in developing a world network of individuals and institutions who share our common ideal. In this article, I shall illustrate the value of partnership in the scientific enterprise as I have lived it.

Science has flourished at different periods of human history in various parts of the globe, first in Ancient Greece (including Egypt, southern Italy, Turkey and Syria) and later in China, India, Persia, Arabia, Turkey and Afghanistan until 1100 AD, when Europe started to appear on the scientific scene. It was only after 1450 that the countries which are now called the Third World started losing ground with respect to Europe.

Nowadays, science is carried out mainly in the Western World and in Japan. The practice of science has become expensive, particularly what is called 'Big Science', for example the study of the ultimate structure of matter, which is pursued in large particle accelerators like those in the USA or at the European Organization for Nuclear Research (CERN) in Geneva, or the study of space. Costs of such enterprises are so high that single countries cannot undertake these efforts alone. They must pool their funds, their scientists and their technological know-how. Equipment in less spectacular fields of science can also be expensive. For instance, high-pressure equipment for catalysis studies in chemistry can be worth several million dollars, not to speak of the cost of fast computers needed for weather forecasting and for climatology research. Spectacular progress has been achieved in the West because of the economic affluence which followed its supremacy in technology, in manufacturing and managerial organization, and of the political will of governments to support either Big Science in a cooperative fashion with other nations, or domestic research in the universities or in specialized institutions. It should also be noted that although progress in science may be achieved through breakthroughs by towering individuals, advances in research are also due to collaborative work by teams which may be made up of as many as dozens or even hundreds of scientists.

Science is also a question of numbers. The number of scientists engaged in scientific research has increased considerably since the end of the Second World War. In 1990, according to UNESCO statistics, the industrialized countries counted 3 600 scientists and engineers engaged in research and in research and development per million population, with Japan and Israel leading with 5 500. On the other hand, the scientific panorama in the developing countries is totally different from the quantitative viewpoint. As a whole, the Third World can only muster approximately 200 scientists and engineers per million population. The gap between North and South is as abyssal from this point of view as it is from the economic and quality of life side.

Besides the large countries like India, Brazil, Argentina and a few others, no country has a sufficient number of scientists to reach a 'critical mass', that is to say the number of researchers who through their work, and their interactions with colleagues from within their own country or from elsewhere, would be in a position to produce significant results on a continuing basis.

In the colonial era, the scientific base of what is now called the developing world was non-existent, except for a few notable individuals like Bose and Rahman in India. When most of these countries became independent in the 1960s, they had to start building their higher education and research practically from scratch.

It was precisely in those days that I began to ponder over the present and the future of science in my own country and in the other developing nations. Coming back to my native Pakistan in 1951 after taking my PhD in theoretical physics at Cambridge and after a research period at the Princeton Institute for Advanced Studies, I began to teach at the Lahore Government College. In this position, I found myself desperately isolated. As the only theoretical physicist in the country, I had no one in my vicinity to talk to, to discuss or to share ideas with. The academic climate was not stimulating at all. After three years, I realized that staying any longer would not make sense; my work would deteriorate, the harvest of my achievements in physics would go to waste and I would be of no use to my country. I reluctantly decided to return to Cambridge, joining the club of the many Asians and Latin Americans who before me had chosen to migrate to the more stimulating research institutions of the North. I sailed back to Europe with the determination to invent something that I could present to the men and women of the developing countries who were faced with the dilemma of either staying in their home country and dying professionally or migrating to the North and remaining competitive scientifically. From those days onward, my working schedule became divided into two parts: one for research and one to think of ways to combat the brain drain and to help scientists from the developing South to give the full measure of their talent. From Cambridge, I moved to Imperial College in London, where the Department of Theoretical Physics was founded in 1957.

During all this time, I dreamed of a place where theoreticians from both the developing and the industrialized countries could work together, in a stimulating environment for research, with a good library and, for those who need them, good computing facilities. This dream started to materialize in 1960 when, as the representative of the Government of Pakistan at the General Conference of the International Atomic Energy Agency (IAEA) in Vienna, I proposed the creation of an International Centre for Theoretical Physics (ICTP). This was a first step towards a large movement of partnership between organizations, governments and individuals. After the International Centre for Theoretical Physics, my efforts were geared towards the creation of the Third World Academy of Sciences (TWAS), the Third World Network of Scientific Organizations (TWNSO) and the International Centre for Science and High Technology (ICS). The setting up of the International Centre of Genetic Engineering and Biotechnology with seats in Trieste and Delhi, in 1983, was also inspired by and large by the ICTP model.

THE INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS OF TRIESTE

Creating a centre as I envisioned it was, for the IAEA, quite an unusual proposition in those days. While the proposal was enthusiastically supported by the developing countries, it met with the indifference of the industrialized countries, with the exception of the then USSR, Denmark and Italy. A preliminary study was made by eminent physicists and, following their recommendation, an international seminar on theoretical physics was held in the summer of 1962 in an outbuilding of the Miramare Castle in Trieste. This seminar proved to be a successful testing ground for the new centre. Finally, after several debates at the IAEA Board of Governors and General Conference, the ICTP was set up in a provisional seat in Trieste, Italy, with an annual budget of US$300 000 provided by the Italian Government, US$55 000 by the IAEA and US$20 000 by UNESCO.

Offers to host the ICTP had been received from several countries, but the package submitted by the Italian Government and the local Trieste authorities was by far the most attractive. It included, in addition to a contribution towards the functioning of the Centre, the provision of a new building (which was made available in 1968) and a first collection of scientific books and journals for the library. Later, the Italian authorities were to provide a guest house for 100 people (1983) and for the doubling of the capacity of the first building in 1989. A third building, which will host all services of the ICTP, and also financed by the Italian Government, is presently under construction in the vicinity of the main building.

The ICTP took off rapidly as a multidisciplinary research centre of excellence. Outstanding results in high energy physics and in plasma physics were published during the very first month of existence of the new centre. Eminent physicists from the advanced countries were lured by the prospect of working in a place where they could discuss with colleagues from the Third World, share their experience and help those who needed their advice. In those Cold War days, theoreticians from the Soviet Union worked together with specialists from the USA and Western Europe for about two years, in plasma and fusion physics – a field which had for a long time been classified. The scientific reputation of the ICTP was established right from the beginning.

The necessary condition for the Centre to be useful to the scientists of the Third World was also accompanied from the ICTP's inception by the development of several modalities which were created to help physicists from the developing world to be able to resist the temptation of migrating to the attractive institutions of the industrialized countries, and to be trained at the highest possible level in research fields for which there were no opportunities in their home country.

The associateship scheme was the first of these modalities. An ICTP associate member is a physicist or mathematician from and living in a developing country who has already achieved important results in his or her discipline, and who is entitled by appointment to periodic visits to the ICTP spread over six years. As a norm, associates pay three such visits to the ICTP, each lasting not less than six weeks and no more than three months, with travel and board supported by the ICTP. In principle, these six-year appointments can be extended but, in practice, budgetary reasons impose limits on the number of extensions, since the roster of applicants is very large. While at the ICTP, associates benefit from all facilities offered by the Centre, i.e. interaction with colleagues, the library and computing facilities if they need them. They have no other obligation than to their own research. This guaranteed possibility of refreshing one's knowledge and accumulating ideas which will be worked out and developed at the home institution have proved to be an efficient deterrent against the brain drain. Former associate researchers with outstanding achievements may be appointed as honorary associates. These can use a fixed sum at their disposal for five years for short visits to the ICTP when their travel is supported by other sources.

For less experienced scientists, the ICTP designed high-level training courses – initially in nuclear and condensed matter physics – and a cost-sharing arrangement with institutions known as the federation scheme. Federated institutions are given the opportunity to depute their younger scientists to the ICTP for a total number of days per year which varies from 40 to 120, depending on the geographical distance from the institution to Trieste. These visits are used for participation in research workshops or in courses, or for meeting experts, collecting scientific data in the library, or using the computing facilities, when these are not adequate in their home country. Boarding expenses of the scientists are borne by the ICTP, while travel is normally paid for by the institution.

Again, this arrangement, which is renewed annually, provides federated institutions with the assurance of regular contacts with a dynamic research centre and, as a consequence, opportunities for maintaining and improving their research standards. Some of these institutions (20 for the time being) have been granted special status in recognition of their scientific achievements. Known as affiliated centres, these are granted US$20 000 per year for five years for the further improvement of their research capacity.

In 1970, the participation of UNESCO in the running of the ICTP was formalized in an agreement with the IAEA. Through UNESCO's partnership, the ICTP was able to expand the sphere of its activities beyond the domains related to the mandate of the IAEA, i.e. those disciplines bearing by and large on the peaceful application of nuclear energy. Thus through the years, new topics were added to the curriculum of the ICTP. In the last decade, the ICTP has held, each year, from 40 to 50 high-level courses, research workshops and conferences on subjects including fundamental physics (high-energy and particle physics, relativity, cosmology and astrophysics), condensed matter physics (solid state, atomic and molecular physics, materials and statistical mechanics), mathematics, physics and energy (nuclear, plasma and fusion physics and non-conventional energy), physics and environment (geophysics, climatology and meteorology, physics of oceans and atmosphere, desertification and soil), physics of the living state (neurophysics, biophysics and medical physics), applied physics (microprocessors, communications, optical fibres, lasers, superconductivity and computation physics) and physics teaching. Courses and workshops bring together from 60 to 80 participants from developing countries and last an average of four weeks. They are designed to bring the participants from a basic knowledge of the topic to state-of-the-art issues with hands-on activities, if need be in the laboratories of microprocessors, laser and fibre optics and high-temperature superconductivity, or with the ICTP mini-computer and the numerous personal computers available at the Centre.

By and large, ICTP courses and workshops address the needs of the theory-minded. For the experimentalists, a training-for-research programme in Italian laboratories was launched in 1983. This programme, which was initially financed by the Italian Department of Cooperation for Development, enables each year 70 to 80 scientists from the Third World to spend from several months to one year in academic or industrial laboratories located in Italy. The Italian National Institute of Nuclear Physics (INFN), the National Council of Research (CNR) and the National Authority for Energy and Environment (ENEA) provide additional fellowships tenable in their laboratories. Some 300 laboratories are in a position to welcome fellows.

Scientists from the developing countries must gain self-confidence and should be encouraged to build up scientific communities in their own countries and regions. To this end, an Office of External Activities was instituted in 1985, which provides intellectual and financial assistance in the organization of courses, workshops, conferences and science teaching seminars, and of visits of scholars in the developing countries themselves. Each year some 100 grants are provided for that purpose.

In the last 10 years, research at the ICTP has been considerably strengthened. The Centre now counts several long-term senior researchers in high-energy, condensed matter, plasma physics and mathematics. They are in charge of the guidance of post-doctoral scientists and, together with visitors, assist other scientists like the associate researchers. They also teach on the recently created diploma courses in theoretical physics and mathematics.

Every year the ICTP welcomes more than 4 000 scientists from the Third World and from the industrialized countries. The average duration of stay of the latter is of the order of 10 days, while the former stay for about five weeks. More than 300 scientific papers are published each year by ICTP staff and visitors. Altogether, since 1964, the number of scientists from developing countries who have taken part in ICTP activities in one capacity or another amounts to 35 000, out of a total of 50 000 visitors. The success of the ICTP and its impact on research conditions in the Third World is due to the close partnership between the international organizations (the IAEA and UNESCO), the Government of Italy (which provides 90% of the budgetary resources of the ICTP), other organizations like the Swedish International Development Agency (SIDA), the local authorities of Trieste and the world scientific community as a whole.

A tripartite agreement between the Government of Italy, the IAEA and UNESCO, committing the administrative supervision of ICTP to UNESCO, was recently signed and is awaiting ratification by the Italian Parliament.

Regrettably, the ICTP has remained essentially a one-off enterprise. So far, to our knowledge, there is no other centre conceived on the same scale that emulates the ICTP, apart from one that is in the process of being set up in the USA.

THE THIRD WORLD ACADEMY OF SCIENCES

Scientists of the Third World must unite their forces. Without such unity, science in the developing countries cannot assert itself in the globalization of science and technology that we are witnessing nowadays. With this objective in mind, I discussed, in 1981, with my co-fellows of the Pontifical Academy, the idea of creating an Academy of Sciences for the Third World. Two years later, the TWAS was founded and, in July 1985, it was officially inaugurated by the Secretary-General of the United Nations, Javier Perez de Cuellar.

The main purposes of TWAS are to recognize and support excellence in scientific research performed by individual scientists from the Third World, to provide promising scientists in the developing countries of the South with conditions necessary for the advancement of their work, to promote contacts between research workers in developing countries of the South and with the world scientific community, to provide information on and support for scientific awareness and understanding in the Third World, and to encourage scientific research on major Third World problems.

At present, the Third World Academy of Sciences counts

311 members from 54 developing countries, including nine Nobel Prize Laureates of Third World origin. TWAS is a non-political and non-profit organization. It became a scientific associate of the International Council of Scientific Unions (ICSU) in 1984 and was granted official NGO status by the United Nations Economic and Social Council (ECOSOC) in 1985. Since 1991, UNESCO has been responsible for the administrative supervision of the Academy. The budget of TWAS is about one-tenth that of the International Centre for Theoretical Physics. Nevertheless, the Academy has successfully launched several programmes in line with its objectives. These programmes include:

TWAS awards (US$10 000) in biology, chemistry, mathematics, physics and medical sciences to individual scientists from developing countries who have made outstanding contributions to the advancement of each of these fields.

Prizes to young scientists in developing countries instituted by academies and research councils in the Third World. TWAS offers financial assistance in this respect.

TWAS research grants, up to a maximum of US$5 000, for promising scientific research work and projects carried out in the Third World.

Provision of spare parts for scientific equipment for laboratories which need them (not more than US$500 each).

South-South fellowships providing travel support for visits to scientific institutions within the Third World for a minimum period of four weeks while living expenses are borne by local sources. Governments and scientific organizations in Argentina, Brazil, Chile, China, Colombia, Ghana, India, the Islamic Republic of Iran, Kenya, the Democratic People's Republic of Korea, Madagascar, Mexico, the Philippines, Syria, Venezuela, Viet Nam, the West Indies and Zaire have followed this programme for a total of over 200 visits. Moreover, TWAS and the Chinese Academy of Sciences have launched a fellowship programme for training young scientists from Third World countries in Chinese laboratories for periods between one month and one year. A similar arrangement has been concluded with the Council of Scientific Research (CSIR) of India which also includes fellowships for postgraduate studies.

Support for international meetings in the developing countries in the form of travel grants to speakers from abroad and/or to participants in the region. These meetings deal with agriculture and biochemistry, biotechnology, chemistry, geology, engineering and medical science.

A joint lectureship programme run in collaboration with ICSU, UNESCO and the Commonwealth Science Council (CSC) whereby scientists from developing countries are provided with opportunities for discussion and cooperation with eminent colleagues from other countries.

A joint fellowship programme in collaboration with UNESCO enabling scientists from developing countries to work in molecular biology laboratories participating in the Human Genome Project. Located in the developed countries, the receiving laboratories provide the visiting fellows with general training in molecular biology analytical techniques with special emphasis on methods essential for sequencing the human genome.

Provision of books and journals donated by individuals and institutions from the industrialized world to scientific libraries in the Third World.

The Academy holds a general conference every second year. The last one was hosted by the Government of Kuwait in November 1992. In addition to discussion of the business of the Academy, general conferences are an occasion for members to meet and interact, for the presentation of the TWAS awards, and for panel discussions and topical conferences on issues of science and technology in the region where the conference is held. Previous general conferences were held in Trieste (1985), in China (1988) and in Venezuela (1990).

THIRD WORLD NETWORK OF SCIENTIFIC ORGANIZATIONS

TWAS collaborates with and hosts the central office of the Third World Network of Scientific Organizations (TWNSO), a network of 26 ministries of science and technology, 39 science academies, 42 science councils and 20 other organizations from 69 developing countries.

TWNSO was created in 1988 with the following objectives: to encourage adequate resource allocations for S&T by governments in the South; to promote the integration of S&T in the national development plans of Third World countries; to further the South's contribution to, and involvement in, global science projects and frontier S&T programmes; to promote the development of collaborative programmes between research institutions in areas of science, technology and environment of critical importance to the development of the South; to recognize and encourage scientific and technical innovations of substantial benefit to economic and social development in the South.

The Network awards two annual prizes in agriculture and technology (US$10 000 each) to institutes or individuals whose scientific and technical innovations have provided significant and sustainable solutions to the problems of the Third World, and provides financial support to its members for instituting annual prizes for promoting the public understanding of science. Moreover, TWNSO publishes a yearbook providing information on the programmes of its members and is preparing an inventory of research and learning institutions of excellence. Regional Offices of TWNSO have been established in Africa (Lagos, Nigeria), the Arab Region (Tunis), Latin America and the Caribbean (Mexico) and Asia and the Pacific (Kuala Lumpur, Malaysia). Two chapters, in the UK and in the USA, provide a link between TWNSO and the scientific institutions of the industrialized countries.

THE INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY

Though the International Centre for Theoretical Physics has gone a long way in training young men and women in pure and applied sciences, for developing countries to become more involved in technological progress another type of training and research institution had to be created. Technology, and especially technology with a high scientific content like that which underlies the communications, laser, pharmaceutical and new materials industries, is a source of wealth for those countries which master it. Training scientists and engineers in these fields can of course be done in institutions of the advanced countries, but the risk of those who are trained in this way being 'brain drained' is very high because of the attraction exerted by economic conditions offered by the local industries.

I therefore conceived a place where scientists from the Third World could be trained for research in domains at the interface between pure science and industrial research and development (R&D), under the aegis of a United Nations organization. 1 presented my proposal for a new centre in Trieste to the Minister of Foreign Affairs of Italy in February 1988. Four months later, funds were released from the Italian Government for a feasibility study of the project, which was made under the guidance of the United Nations Industrial Development Organization (UNIDO) as the executing agency. The study was carried out in consultation with renowned scientists from developing countries, Italy and other industrialized countries (and including three Nobel Laureates: K.A. Mueller from Switzerland, K.M. Siegbahn from Sweden and K. von Klitzing from Germany). Following the recommendations formulated during the feasibility study, the Italian Government made funds available for pilot research projects. The second phase started in 1990, the programmes focusing on three main areas: pure and applied chemistry, high technology and new materials, and earth, environmental and marine sciences and technology.

Three international institutes were created corresponding to these areas, and together they presently constitute the International Centre for Science and High Technology (ICS). The International Institute for Pure and Applied Chemistry has research lines on reactivity and macromolecules. The International Institute for High Technology and New Materials is made up of four research lines: photonics, composite materials, superconductors and semiconductors. The third component of the ICS, the International Institute for Earth, Environment and Marine Science and Technologies, has research lines dealing with climate and global change, ecological interactions, geophysical exploration, and with marine sciences and technologies and coastal zone management.

The research work of the ICS is carried out in temporary laboratories located either on the ICTP campus or at the University of Trieste and in the Trieste research area. In

1991-92, the three institutes of the ICS welcomed 66 scientists and trainees in their laboratories for a total of 600 person-months. Research results were published in 63 papers. The ICS has also been very active in the training sector. In 1992, 15 courses, workshops and conferences were organized to train scientists from developing countries in subjects related to the programmes of the research lines. Altogether 958 scientists, of whom 602 came from the Third World, took part in these training activities. The majority of these courses and workshops are held in Trieste but some are also hosted in developing countries. This was the case for a course on mathematical ecology (in Addis Ababa, Ethiopia) in 1992. Argentina, Egypt and India are hosting courses on superconductivity, solar energy and organic synthesis respectively, in 1993. Moreover, among its interdisciplinary programmes the ICS conducts courses on research and innovation management on a regular basis. One of these was held in Moscow, Russia, in 1992. Argentina and Hungary are hosting the 1993 versions.

With limited resources, the ICS has demonstrated its capacity to respond to the needs of the developing countries in a most efficient and flexible way. The results of the pilot projects have already been favourably reviewed by the UNIDO evaluation team, and the ICS is now fully prepared to enter the operational phase as soon as its funding is secured.

CONCLUSION

Looking back over these 33 years of activity, I recognize the quantity and the quality of goodwill and of partnership in various forms that have contributed to the materialization of my ideas. As an international civil servant, I first acknowledge the role and importance of UNESCO and the IAEA in setting up the ICTP in Trieste and in helping the Third World Academy of Sciences, and of UNIDO in launching the ICS. These organizations have provided, in addition to the financial aspect, a framework which facilitated the participation of scientists from all over the world in the programmes of the Trieste institutions and contributed to enhance their visibility.

In addition to these three organizations, others such as the United Nations Development Programme (UNDP), the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP), the World Health Organization (WHO) and the European Economic Community have supported our programmes in one way or another.

Italy has been a formidable partner, its government supporting 90% of the operation of the Trieste institution. Local authorities have also made important contributions. The Italian universities and the University of Trieste in particular have collaborated in various ways with the ICTP, the ICS and TWAS, and so have prestigious national bodies like the INFN, the CNR and ENEA.

Other partners have been the Swedish Agency for Research Cooperation (SAREC), the Canadian International Development Agency (CIDA) and the OPEC Fund. Last but not least, I must mention the world community of scientists – from the South and from the North, from the East and from the West – which has always supported our efforts.

Our presence in Trieste has stimulated other initiatives which are a reality today. One of them is the International School for Advanced Studies, located next to the ICTP. The other is the Synchrotron Light Radiation Laboratory, which is 13 kilometres away and which will start functioning in 1994.

Trieste has been dubbed the 'City of Science'. However, its scientific institutions are still not sufficient to cope with the needs of the Third World. This is why I voiced, at the Third TWAS General Conference in Caracas (1990), the idea of establishing a number of international or regional centres for science, high technology and environment in the developing countries themselves. To date, the Third World Network of Scientific Organizations (TWNSO) has received 33 proposals from 23 developing countries for upgrading existing centres to a level of excellence such that they will be able to operate on a regional basis. All the proposals were submitted by prime ministers or by ministries of science and technology. They will be reviewed in several stages and decisions on their qualifications will be made by a ministerial-level committee. UNIDO is actively participating in this evaluation process. I believe that there is again a great occasion for partnership to manifest itself in all the forms which succeeded in Trieste and I earnestly hope that the world scientific community will, as ever, grasp this opportunity to enhance the solidarity between South and North.

PROFESSOR ABDUS SALAM is founder and Director of the International Centre for Theoretical Physics in Trieste and President of the Third World Academy of Sciences and the Third World Network of Scientific Organizations. He studied at Punjab University in Pakistan and St. John's College, Cambridge. He was Professor at Government College, Lahore, and Punjab University, and has been full Professor at Imperial College, London, since 1957. Among his many awards he can count the 1979 Nobel Prize for Physics, given in recognition of his work on the unification of the electromagnetic and weak interactions, and the Copley Medal in 1990. He is a member of academies and learned societies in 24 Third World and industrialized countries and has been awarded over 40 honorary doctorates from 28 countries. He is the author of several scientific books and many articles on the physics of elementary particles, and on scientific and educational policies for developing countries.

4 RECENT DEVELOPMENTS

MATHEMATICS

Ian Stewart[1]

As the 20th century begins to draw to a close, mathematical research is in an extremely healthy state, with many long-standing problems being solved and many new areas of research emerging. Perhaps the most encouraging aspect of all is that the relation between mathematics and the applied sciences is becoming markedly stronger, with ideas being traded in both directions. The importance of mathematics lies not in its applications to any particular area of science, but in its ability to 'transfer technology' between different areas of application. The technology being transferred is mathematical concepts and techniques, not hardware; but the effect is just as strong. Because mathematical concepts are general, ideas that first become apparent in one area can readily be transferred to another, apparently quite different, area. Examples discussed later will include new developments in knot theory, arising from mathematical physics and applied to molecular biology; a musical problem whose solution has illuminated the theory of waves; an optimization problem that has led to fundamental questions about computability; and a new kind of geometry that originated in classical mechanics and is now of central importance in quantum physics.

Ultimately mathematics proves its value to humanity through practical pay-offs; but many important ideas do not originate in any specific application. They come from the internal needs of mathematics itself. If basic questions cannot be answered, there is a gap in mathematical understanding that will cause difficulty throughout the entire subject, theory and practice alike. So central problems of pure mathematics are just as important as applications in the long run. Mathematics takes its inspiration wherever it can find it.

There are literally hundreds of major areas of mathematics, all the subject of active research, and thousands of well-defined sub-areas. It is not possible to provide a comprehensive overview of the whole of today's mathematical research. Instead, I have chosen six areas that between them represent the scope, power and originality of late 20th century mathematics, and which point the way towards the mathematics of the 21st century. In each case I can offer only a sample of the work that is currently going on. The areas described are knots and low-dimensional topology, non-linear dynamics (popularly known as Chaos Theory), diophantine equations, symplectic geometry, algorithms and complexity, and the spectrum of the Laplace operator ('hearing the shape of a drum').

KNOTS AND LOW-DIMENSIONAL TOPOLOGY

Topology is the study of properties of shapes that remain unchanged by continuous deformations – properties such as connectedness, knottedness, and the presence or absence of 'holes'. For at least a century, topologists have tried to find effective ways to distinguish different knots; but until recently, the only available methods were those introduced in the 1920s. The subject was revolutionized in the 1980s by the discovery of an entirely different approach – the Jones polynomial invented by the New Zealand mathematician Vaughan Jones[1]. Distinguishing knots is a central and important problem, because it is the simplest and most natural case of a very general question, telling the difference between different ways of embedding one space in another. Practical applications of knot theory do exist: they include problems as diverse as Feynman diagrams in quantum physics and the cutting of DNA molecules by enzymes. But the real allure of knots lies in their unexpected subtlety.

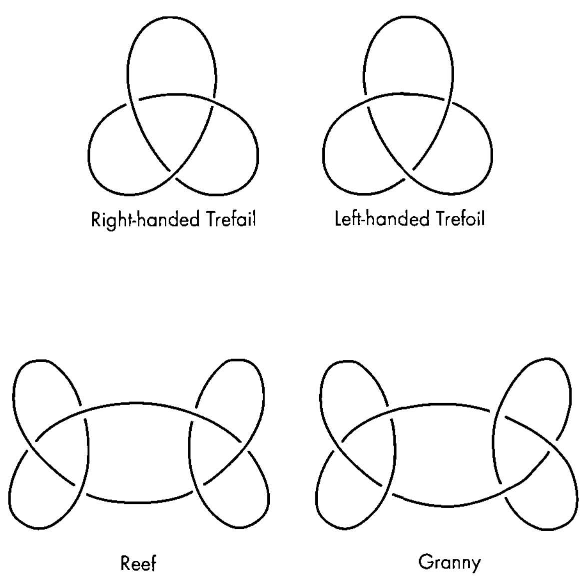
A mathematical knot is a closed loop in three-dimensional space. Two knots are topologically equivalent if one can be continuously deformed into the other, by stretching and bending the space that surrounds them. Anything that deforms to a circle is unknotted; anything else is a genuine knot. It is this freedom to deform knots that makes them so subtle: in order to prove that two knots are different, all conceivable deformations must somehow be ruled out. All known methods boil down to finding *invariants* – properties that remain unchanged by deformations. Knots with different invariants must be topologically different.

The key invariant of the classical period, the 1920s, was discovered by J.W. Alexander. It associates to any knot an algebraic expression, its *Alexander polynomial.* Knots whose polynomials are different cannot be deformed into each other. For example the Alexander polynomial of a trefoil knot is t^2-t+1, whereas that of a figure-eight knot is

[1]University of California at Berkeley, USA

t^2-3t+1. Since the polynomials are different, so are the knots. Unfortunately the converse is not true: knots with the same Alexander polynomial need not be topologically equivalent. Both the trefoil knot and its mirror image have the same Alexander polynomial. And the reef and granny knots (Figure 1) both have Alexander polynomial $(t^2-t+1)^2$, even though they are different – as was classically proved by more esoteric methods.

FIGURE 1
KNOT INVARIANTS



The trefoil and its mirror image are topologically distinct, but have the same Alexander polynomial. The Jones polynomial distinguishes them without difficulty. The same is true of the reef knot and the granny knot.

In 1984 Jones invented an entirely new knot invariant, also a polynomial. He was working in analysis, studying von Neumann algebras, which arise in mathematical physics. He noticed some curious structural features, similar to some classical work by Emil Artin on the theory of braids – many-stranded knots. Following up the similarities led him to a totally unexpected new knot invariant, powerful enough to answer with ease problems that had taxed classical methods almost to their limits. For example, the Jones polynomial for a trefoil knot is $t+t^3-t^4$, whereas that for its mirror image is obtained by replacing t by t^{-1}, giving $t^{-1}+t^{-3}+t^{-4}$, which is manifestly different. Similarly the Jones polynomial for the reef knot is

$$-t^3+t^2-t+3-t^{-1}+t^{-2}-t^{-3}$$

which is obviously different from the Jones polynomial of the granny knot:

$$t^8-t^7+t^6-2t^5+2t^4+t^2.$$

Other mathematicians have since discovered many variations on Jones' method, leading to an at first bewildering array of new knot invariants.

However, these invariants have been greatly illuminated by ideas from several areas of mathematical physics. Jones, early on, noticed an odd connection with statistical mechanics, a subject that on the face of it has nothing at all to do with knots. It arose from physicists' attempts to understand bulk matter – the nature of gases, liquids and solids. The most interesting physics deals with phase transitions – changes of state from solid to liquid or from liquid to gas. Phase transitions do not occur gradually, but suddenly, at very specific temperatures. One way to tackle this phenomenon is to use state models – geometric arrangements whose elements are called *sites*. In 1971, long before Jones began his work, H.N.V. Temperley and E.H. Lieb found a connection between two different types of exactly soluble model in statistical mechanics, called Potts models and ice models. Their explanation of that connection involves von Neumann algebras identical to those investigated by Jones; and in statistical mechanics they are called Temperley-Lieb algebras. A knot diagram can be thought of as a state model. Its sites are its crossings, the interactions are determined by the geometry of the knot that joins them. The strange coincidence of the Temperley-Lieb algebras suggests that we may hope to interpret the Jones polynomial in statistical-mechanical terms. This was done in 1987 by Yasuhiro Akutsu[2] and Miki Wadati[3]. In the same year Louis Kauffman[4] found a statistical-mechanical interpretation of the original Jones polynomial, and used it to answer (affirmatively) a long-standing question of

[2]Kanagawa University, Yokohama, Japan. [3]University of Tokyo, Japan. [4]University of Illinois at Chicago, USA

classical knot theory, known as the Tait conjecture. Many other classical conjectures have succumbed to the new invariants.

These new ideas are important in other areas of science, the most surprising being molecular biology. Four decades ago James Watson and Francis Crick discovered the structure of the DNA molecule, the backbone on which genetic information is stored and manipulated. DNA forms a double-helix like a two-stranded rope; and when a cell divides, the genetic information is transferred to the new cells by splitting the strands apart, copying them, and joining the new strands to the old in pairs. Anyone who has tried to separate the strands of a long piece of rope knows that they tangle up as you pull them apart. The genetic biochemistry must ravel and unravel this tangled thread, rapidly, repeatedly and faultlessly; the very chain of life depends upon it. How?

Biologists tackle the problem by using enzymes to break the DNA chain into pieces small enough to investigate in detail. A segment of DNA is a complicated molecular knot, and the same knot can look very different after a few tucks and turns have distorted its appearance. Until recently biologists had no systematic method for distinguishing these tangled structures, or for working out the associated chemical reactions. The Alexander polynomial, for example, just isn't effective enough. But the new polynomial invariants of knots are far superior, and the topology of knots is now an important practical issue in molecular biology.

A knot, by definition, is intrinsically three-dimensional. But the Jones polynomial and everything that followed it operate on two-dimensional pictures of knots, diagrams in the plane, crossings, overpasses. A truly three-dimensional knot shouldn't 'know about' such things. In 1988 Sir Michael Atiyah[5] challenged mathematicians and physicists to find an intrinsically three-dimensional approach to the Jones polynomial. In 1988 the mathematical physicist Edward Witten[6] found just such a connection, which he called topological quantum field theory. The main consequence is that there is a formula – inspired by statistical mechanics, but now in quantum dress – which is obviously topologically invariant. Buried within this function is a whole bunch of other invariants – including the Jones polynomial and its generalizations. The formula works with the knot itself, embedded in three-space, independent of any two-dimensional diagram or representation, so it answers Atiyah's challenge.

As a bonus, Witten's approach solves another awkward problem: how to generalize the Jones polynomial to knots that are tied not in ordinary three-space, but in an arbitrary three-dimensional manifold. (A manifold is a multidimensional curved 'surface'.) You can even throw the knots away to get new topological invariants for three-dimensional manifolds.

But knots still have more to offer. Even recently, another new knot invariant has been discovered; and it is not a polynomial, but a number. Imagine tying a knot in a long rubber rod. The more complicated the knot is, the more you have to bend the rod to tie it; so the more elastic energy it acquires. But it now seems that the most interesting energy concept for knots is not elastic, but electrostatic – as Shinji Fukuhara[7] suggested in 1987. Imagine the knot to be a flexible wire of fixed length, able if necessary to pass through itself, and provide itself with a uniform electrostatic charge. Because like charges repel, a knot that is free to move will try to keep neighbouring strands as far apart as possible. That is, it will minimize its electrostatic energy. This minimum energy value is an invariant, with several pleasing properties. For example, in 1991 Jun O'Hara[8] proved that the minimum energy of a knot really does increase as the knot becomes more complicated: only finitely many topologically different knots exist with energy less than or equal to any chosen value. There is a natural numerical scale of complexity for knots, ranging from simple knots at the low energy end to more complicated ones higher up.

What are the simplest knots, according to this scale? Steve Bryson[9], Michael Freedman[10], Zheng-Xu He[11] and Zhenghan Wang[12] have recently proved that they are exactly what you would expect. They are 'round circles' – that is, circles in the everyday sense rather than merely the topological. The energy of a round circle is 4, and all other closed loops have higher energy than that. Any loop with energy less than $6\pi+4$ is topologically unknotted. More generally a knot with c crossings (in some two-dimensional projection) has energy at least $2\pi c+4$. (This bound is

[5]University of Cambridge, UK. [6]Institute for Advanced Study, Princeton, USA. [7]Tsuda College, Kodaira, Japan. [8]Tokyo Metropolitan University, Japan. [9]NASA Ames, USA. [10,11]University of California at San Diego, USA. [12]Princeton University, USA

probably not the best possible: the lowest known energy for an overhand knot is about 74.) The number of topologically distinct knots of energy E is at most $0.264(1.658)^E$.

NON-LINEAR DYNAMICS AND CHAOS THEORY

Albert Einstein believed that God does not play dice; that the universe is governed by precise laws rather than chance. The area popularly known as Chaos Theory clarifies the question through a new paradox: precise laws may generate randomness. As a result our cherished beliefs about determinism, predictability, and complexity are back in the melting-pot. For instance, why are tides predictable, but weather not? Tides are caused by the gravitational attraction of the Sun and Moon; weather by the motion of the atmosphere under the influence of heat from the Sun. The law of gravitation is not noticeably simpler than the laws of fluid dynamics, so why can we predict tides years ahead, yet get the weather wrong after a few days?

The clue is such a simple idea that its significance went unnoticed until about 20 years ago. Every cook knows that you can mix egg white very thoroughly just by revolving an egg whisk in a regular and predictable manner. However, if you try to keep track of individual particles of the egg white, you'll find they behave in a very irregular and unpredictable manner. Mixing is a predictable process with an unpredictable result.

In order to understand how simply mixing can arise, we must introduce the general concept of a dynamical system. This is a system that can exist in some state x (which may involve many variables) at each instant of time t. There are two kinds: either continuous-time systems determined by differential equations

$$dx/dt = f(x)$$

or discrete-time systems determined by difference equations

$$x_{t+1} = f(x_t).$$

Here f is a fixed, non-random function. Dynamical systems are deterministic, in the sense that initial conditions uniquely determine all future behaviour. This is most easily seen for discrete-time systems. Given x_0, the state at time $t = 0$, we successively find that

$$x_1 = f(x_0)$$
$$x_2 = f(x_1) = f(f(x_0)),$$

and in general

$$x_t = f^{(t)}(x_0) = f(\ldots f(f(x_0))\ldots) \text{ (t occurrences of f).}$$

This process is known as iteration of the function f. The continuous case is more subtle, and requires uniqueness theorems for the solutions of differential equations.

How can a deterministic rule lead to random behaviour and mixing? One of the simplest examples occurs when the state x is a number, written as a decimal, and the function f is 'chop off everything before the decimal point and multiply by 10'. That is,

$$f(x) = 10(x-[x])$$

where [ ] denotes the integer part. This system displays several kinds of dynamics: some regular, some chaotic. For example when $x = 10/3 = 3.3333...$, we drop the initial 3 to get 0.3333..., then multiply by 10 to get the original 3.3333... back again. So $f(10/3) = 10/3$, and this particular starting value is a steady state of the dynamics. If instead we start with the fraction $40/33 = 1.212121...$, whose digits alternate, then the first application of the rule leads to 2.121212... and a second application leads back to 1.212121... again. This time the dynamic is periodic, with period 2.

To get more complex behaviour, start with the number $\pi = 3.1415926535...$, whose digits never repeat. Successive states of the system are

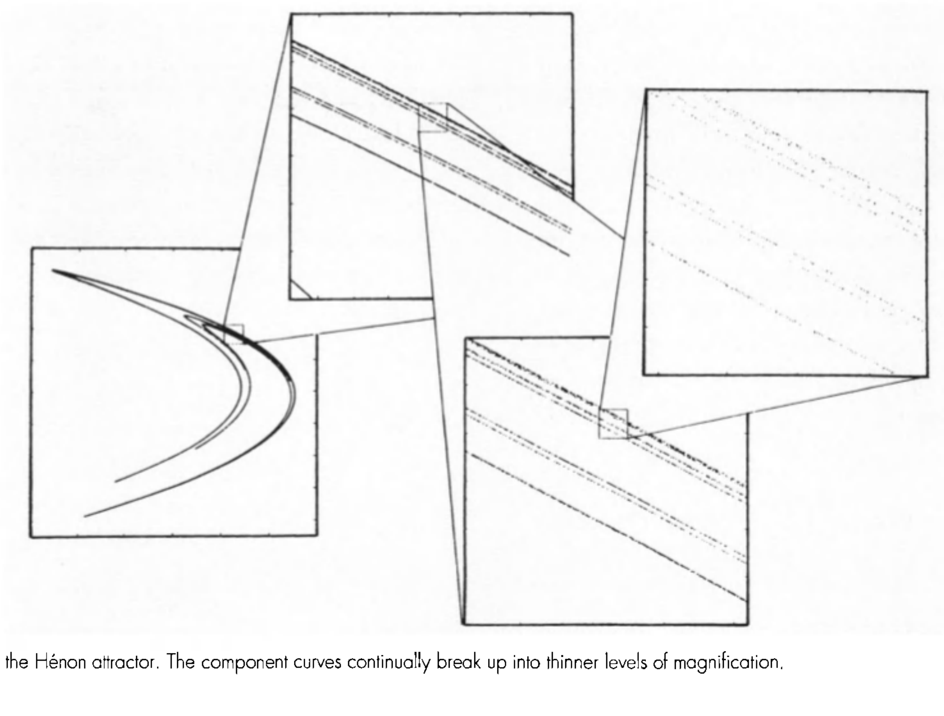
$$x_0 = 3.14159265...$$
$$x_1 = 1.41592653...$$
$$x_2 = 4.15926535...$$
$$x_3 = 1.59265358...$$
$$x_4 = 5.92653589...$$
$$x_5 = 9.26535897...$$

and so on. The decimal digits move one place left at each step: the one on the front is chopped off. Because the digits of π never fall into a repetitive cycle, neither does the dynamics. It is not a steady state, nor is it periodic.

Think about using this rule to predict the successive numbers that occur. Suppose that instead of π, we take a starting value π' that is identical to π until the millionth decimal place, but thereafter differs from it in an arbitrary manner. The number π' is a very good approximation to π, far closer than any physical measurement can be. And for many iterations of the dynamical rule f, the two sets of predictions are almost the same. But that error is creeping steadily leftwards along the numbers. After one time-step it is not in the millionth place, but in the 999 999th. After two, in the 999 998th. After 999 999 repetitions it has appeared in the first decimal place and the prediction with π' as starting value differs considerably from that obtained by taking π as the starting value. The next value could be... anything. It depends on what the 1 000 001st decimal place of π' is. From this point on, the predictions based upon π as the initial state, and those based on the incredibly accurate approximation π', are totally independent. It might seem that there is no problem with a prediction that starts to go wrong after a million steps. But if you're trying to predict the winner of a horse race, and each time-step in the calculation is a millionth of a second, then you've lost track of your horse before it's left the starting gate.

The reason for this effective unpredictability is that the states of the system are continually being stretched apart, but folded back into the same confined space – mixing them up just as kneading mixes up bread dough. Any system of this kind will exhibit *chaos* – apparent randomness in a deterministic system. The equations for tides are non-chaotic dynamical systems: long-term prediction works fine; but those for weather are chaotic. The difference between a chaotic system and a non-chaotic one is very simple. In classical dynamical systems, errors in initial states do not grow very rapidly. In chaotic systems, they grow exponentially. At some point in the future, depending on the size of the error and the time-step for the prediction, the error becomes larger than the true prediction, and from that moment on the prediction that

FIGURE 2
THE HENON ATTRACTOR



Fine structure of the Hénon attractor. The component curves continually break up into thinner levels of magnification.

you make has no useful relation to the actual behaviour.

Although chaos is unpredictable, it also possesses strong elements of stability, as can be seen by representing dynamics geometrically. The set of states x forms a space, called the phase space of the system. As an initial point changes in time, it moves through phase space, describing a curve (continuous time) or sequence of points (discrete time) called its orbit. Many systems possess one or more attractors: geometric objects in phase space towards which the orbits of all points that start nearby tend. A steady state is a point attractor; the attractor corresponding to a periodic orbit is a closed loop or cycle. Chaotic attractors are usually fractals – geometric shapes with fine structure on all scales. For example, the Hénon system

$$f(x,y) = (1 - ax^2 + y,\ bx)$$

where a and b are constants, has (for some values of these parameters, notably $a = 1.4$, $b = 0.3$) an attractor that resembles a rather fuzzy parabola. Computer simulations suggest that when the attractor is magnified, what appear to be individual curves break up into ever more layers (Figure 2). An important recent development is the proof, by Michael Benedicks[13] and Lennart Carleson[14], that this is indeed the case – at least, for small enough b and a set of values of a of non-zero measure.

Attractors are stable in the sense that nearby initial points have orbits that approach them indefinitely. The chaos occurs in the motion on the attractor; the motion towards it is steady and relentless. Different types of chaos occur for different attractors.

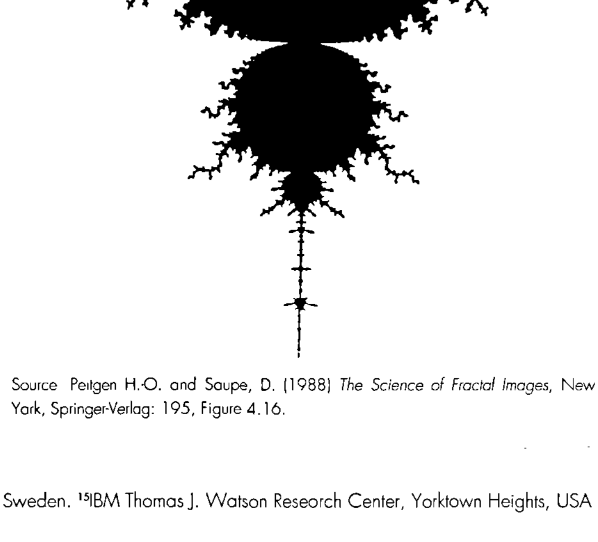
There are many applications. Chaos caused by Jupiter's gravitational field can fling asteroids out of orbit, towards the Earth. Disease epidemics, locust plagues, and irregular heartbeats are more down-to-earth examples of chaos. Chaos in turn is a part of one of the major growth areas of current mathematical research: the theory of non-linear dynamical systems. (A system is *non-linear* if the function f is not just a linear combination of the coordinates of the state x, such as $2x_1 + 5x_2 - x_3$. The Hénon system, for instance, involves a non-linear term x^2.)

A striking feature of chaos is that it generates very complex behaviour from simple rules. The function $f(x) = 10(x - [x])$ is very simple; but the successive digits of π, which show up when you iterate f with π as initial condition, are extraordinarily complicated. There is *no* recognizable pattern to them. The most famous icon of chaos, the Mandelbrot set – named after its inventor Benoit Mandelbrot[15], the founder of the theory of fractals – demonstrates this point even more dramatically. It results from the even simpler function

$$f(z) = z^2 + c$$

where z is a complex number and c is a complex constant. For each value of c, start with an initial value $z = c$, and iterate f. The Mandelbrot set M is the set of all c such that the values remain bounded. It looks a bit like a cross between a cat, a cactus, and a tree in winter (Figure 3). The Mandelbrot set has an infinitely complicated boundary. If you look at a small region near the boundary and magnify it, you see ever tinier complicated geometric structures – spirals,

FIGURE 3
THE MANDELBROT SET



Source Peitgen H.-O. and Saupe, D. (1988) *The Science of Fractal Images*, New York, Springer-Verlag: 195, Figure 4.16.

[13,14]Royal Institute of Technology, Stockholm, Sweden. [15]IBM Thomas J. Watson Research Center, Yorktown Heights, USA

THE 1990 FIELDS MEDALLISTS

There is no Nobel Prize for mathematics. But there is an equivalent, in prestige if not in monetary value, known as the Fields Medal, which was endowed by the Canadian mathematician J.C. Fields and is awarded every four years, on the occasion of the International Congress of Mathematicians (ICM). A comparable award for research in computer science, known as the Rolf Nevanlinna Prize, is also made at the ICM. At the most recent congress, held in 1990 in Kyoto, Japan, four Fields Medals and the Nevanlinna Prize were awarded. The names of the recipients and a brief description of their work follow.

FIELDS MEDALS

Vladimir Drinfeld, of FTINT Kharkov, Russia, for his work on the Langlands Programme towards an understanding of the Galois groups of local and global fields of dimension 1; the classification of instantons; Quantum groups – an exciting generalization of classical Lie groups, carried out within the framework of Hopf algebras.

Vaughan Jones, of University of California at Berkeley, USA, in recognition of his work on the index theorem for von Neumann algebras, its relation to new knot invariants (discussed in this chapter), and their relation to statistical mechanics and quantum groups.

Shigefumi Mori, of Kyoto University, Japan, for the classification of three-dimensional algebraic varieties – the three-dimensional analogues of curves and surfaces defined by polynomial equations.

Edword Witten, of Institute for Advanced Study, Princeton, USA, for his work on supersymmetry and Morse theory, the index theorem for the Dirac operator, rigidity theorems in string theory, intrinsic interpretations of knot invariants by way of topological quantum field theory (discussed in this chapter) and proof of positivity of energy in Einstein's theory of gravitation.

NEVANLINNA PRIZE

Alexander Razborov, in recognition of his derivation of lower bounds for the complexity of various computational problems, based upon Boolean circuit models.

blobs, seahorses, fans, curlicues, trees, crystals, tracery and so on (see Figure A, colour section p. i). This small-scale intricacy – beautiful but unpredictable and, as we shall see below, uncomputable – goes on forever. The boundary of the Mandelbrot set is a fractal. Associated with any fractal is a number, its Hausdorff-Besicovich dimension, a measure of how it behaves under scaling, or of how rough it is. Mitsuhiro Shishikura[16] has recently proved that the Hausdorff-Besicovich dimension of the boundary of the Mandelbrot set is precisely 2. This implies that some regions of the boundary are almost as crinkled as a space-filling curve.

The picture is extremely complicated; but the process that generates it is simple. Science tries to infer laws of nature from observations of their consequences; and the Mandelbrot set illustrates an important point. The observations may look complicated even though the laws that lie behind them are simple. This encourages us to seek simplicity within apparently complex data. Chaos teaches an important lesson for the whole of science.

DIOPHANTINE EQUATIONS

One of the most notorious unsolved problems in mathematics is Fermat's Last Theorem, which dates from about 1650. The lawyer and brilliant amateur mathematician Pierre de Fermat wrote it in the margin of his copy of Diophantus's *Arithmetica*. In modern notation it asserts that the Fermat equation

$$x^n + y^n = z^n$$

has no integer solutions $x, y, z \neq 0$, whenever n is an integer ≥ 3. Equations to be solved in integers are called Diophantine equations. Over the centuries various mathematicians proved special cases: Fermat himself proved his conjecture true for $n=4$, Euler for $n=3$, Dirichlet and Legendre for $n=5$. Ernst Kummer developed the algebraic theory of ideals in order to extend the range of values for which the theorem can be proved. It was known that Fermat's Last Theorem is true for all $n \leq 4\,000\,000$, thanks to a recent computer-assisted investigation by Joe Buhler[17], Richard Crandall[18], Tauno Metsänkylä[19] and Reijo Ernvall[20].

If (x,y,z) solves the Fermat equation, then so does

[16]Tokyo Institute of Technology, Japan. [17]Reed College, Portland, USA. [18]NeXT Computer Inc., Redwood City, USA. [19,20]University of Turku, Finland.

(cx, cy, cz) where c is any integer. A solution is therefore called primitive if x, y and z have no common factor. Until recently we knew that if an exception to Fermat's Last Theorem exists, for some $n \geq 3$, then there are only finitely many primitive solutions for that exponent n. This knowledge came about as a result of a major breakthrough in the theory of Diophantine equations. Rewrite Fermat's equation as

$$X^n + Y^n = 1$$

where $X = x/z$ and $Y = y/z$. Rational solutions of this two-variable equation correspond precisely to integer solutions to Fermat's equation. Now an equation $f(X,Y) = 0$ in two variables can be thought of as defining a complex curve, which as a real object has two dimensions and this defines a surface. This surface is topologically equivalent to a torus with g holes, where g is a number called the genus. In 1922 Leo Mordell noticed that the only equations $f(X,Y) = 0$ that were known to have infinitely many rational solutions were those for which f has genus 0 or 1. He stated the Mordell conjecture: if the genus of f is 2 or more, the number of solutions is finite. The genus of the Fermat equation is $\frac{1}{2}(n-1)(n-2)$, which is bigger than 1 when $n \geq 3$. So the Mordell conjecture implies that the number of primitive integer solutions of any Fermat equation is finite. In 1983 Gerd Faltings[21] proved the Mordell conjecture, one of the major mathematical events of modern times. Since then D.R. Heath-Brown[22] proved that Fermat's Last Theorem is almost always true: the proportion of integers n for which there are no solutions approaches 100% as n becomes large.

In June 1993 came the astonishing announcement that Fermat's Theorem had been proved, in full, by Andrew Wiles of Princeton University. The proof, variously reported as occupying between 200 and 1 000 pages, approaches the problem from the same general viewpoint as Faltings. In the 1980s Ken Ribet, building on the work of Jean-Pierre Serre, studied curves of the form $Y^2 = X(X - x^n)(Y - y^n)$ where (x,y,z) is a supposed solution of the Fermat equation. This is an example of a so-called *elliptic curve*, a curve of the form $Y^2 = aX^3 + bX^2 + cX + d$. A great deal is known about the arithmetic of elliptic curves. By using this powerful theory, Ribet proved that Fermat's Last Theorem would be a consequence of the Weil-Taniyama Conjecture, that any elliptic curve defined over the rational numbers can be parametrized by elliptic modular functions. (This is analogous to the parametrization of the circle $X^2 + Y^2 = 1$ by the trigonometric functions: $X = \sin\theta$, $Y = \cos\theta$.) Wiles proves a special case of the Taniyama Conjecture, for 'semistable' curves, and shows that this is good enough to prove Fermat's Last Theorem. The full Weil-Taniyama Conjecture remains open. Wiles' proof still needs to be checked, but most experts appear to be convinced.

Since it is not possible for two cubes to sum to a cube, might it be possible for three? It is; in fact $3^3 + 4^3 + 5^3 = 6^3$. Leonhard Euler conjectured that for all n it is possible for n nth powers to add to an nth power, but impossible for $n-1$ to do so. However, Euler's conjecture is false. In 1966 L.J. Lander[23] and T.R. Parkin[24] found four fifth powers whose sum is again a fifth power:

$$27^5 + 84^5 + 110^5 + 133^5 = 144^5.$$

In 1988 Noam Elkies[25] found the first counterexample to Euler's conjecture for fourth powers:

$$2\,682\,440^4 + 15\,365\,639^4 + 187\,960^4 = 20\,615\,673^4.$$

He did this by making a careful study of the surface $x^4 + y^4 + z^4 = 1$. Using a general procedure for constructing new rational solutions from old ones, he proved that rational points are dense on this surface. There are, in short, infinitely many integer solutions.

After Elkies had discovered that a solution existed, Roger Frye[26] found the smallest possible one by computer search:

$$95\,800^4 + 217\,519^4 + 414\,560^4 = 422\,481^4.$$

Many questions about Diophantine equations remain unanswered; but there are plenty of new ideas around to help.

SYMPLECTIC GEOMETRY

The motion of matter is one of the richest sources of mathematical concepts. It is possible to trace a continuous thread from the experiments of Galileo Galilei and the

[21]Princeton University, USA. [22]University of Oxford, UK. [23]*Affiliation not known.* [24]*Affiliation not known.* [25]Harvard University, USA. [26]Thinking Machines Corporation, USA

empirical laws of Johannes Kepler, by way of Isaac Newton, Joseph-Louis Lagrange, and the optical/mechanical analogies of William Rowan Hamilton, to a large part of the mainstream of present day mathematics: differential equations, manifolds, Lie groups, measure theory, quadratic forms, Fourier series and functional analysis, for example. But the concept that potentially is the furthest reaching of all is inspired by a geometric interpretation of Hamilton's general formalism for mechanics, known as symplectic geometry. Its importance for mechanics is now clear, thanks in particular to the efforts of the Russian and American schools of dynamical systems over the last three decades. But a broader movement is now gathering momentum. Vladimir Arnold[27] has laid down what might be termed the manifesto of symplectic mathematics – the applied mathematics of the 21st century.

CONTROVERSY OVER COMPUTERS

With the advent of computers with huge memories, rapid arithmetic and good graphics, mathematics has acquired a powerful experimental tool. Mathematicians can try out special cases of problems, and see what answers the computer comes up with. Then they can think about the patterns revealed by those experiments, and try to prove that they occur in general. However, experiments – even extensive ones – can be misleading. For example, computer experiments show that up to limits of several billion there are fewer primes of the form $4k+1$ than $4k+3$. This might seem compelling evidence; but in fact it has been proved that eventually the $4k+1$ primes catch up. An early theorem in this direction proved that the $4k+1$ primes gain the lead before $10^{10^{34}}$, a number so huge that it would never be found by direct experiment.

There is nothing especially radical about experiments in mathematics. For example, Carl Friedrich Gauss' notebooks contain innumerable calculations in which he tried to guess the answers to problems in number theory; and Isaac Newton's papers also contain many experimental calculations. The novelties are the computer, which can perform large numbers of experiments beyond the capacity of the unaided human brain; and the willingness of mathematicians to be much more explicit about their use of experiments. They now publish the experiments even though rigorous proofs are lacking. Indeed a new journal of experimental mathematics has been started.

Experimental mathematics is controversial. Some mathematicians, among them Steven Krantz, Washington University, USA, and John Franks, Northwestern University, Evanston, USA, dislike the approach intensely, and have written articles condemning it. They believe that it is damaging the integrity of the subject. They point out that experiments can mislead: for example pictures of the Mandelbrot set make it appear disconnected, whereas in fact it is connected.

The advocates of experimental mathematics, including Mandelbrot himself, argue that the opposition hasn't done its homework. They believe that it is valuable for research mathematicians – especially the coming generation – to see not just polished proofs, but the evidence that led to them. They point out that all experiments require careful design and interpretation. When Mandelbrot first drew his set he observed some tiny specks, separated from the rest of the set. But anyone who works with computer graphics soon finds out there may be invisible fine structure below the limits of resolution of the pictures. Indeed, Mandelbrot conjectured that the set was connected; and it became a well-known problem.

Eventually, John Hubbard, University of Richmond, USA, and Adrien Douady, University of Paris-Sud, Orsay, France, gave a rigorous proof that the Mandelbrot set is indeed connected. Hubbard has explained that the computer pictures played an important role in finding a proof. These pictures represented the set by multicoloured contours, which – it turns out – do not surround the specks, as they would if the specks really were disconnected. Instead, they seem to nestle around thin filaments that run between the specks and the main body of the Mandelbrot set. Far from being misleading, this experimental evidence pointed directly at the truth.

The resolution of this controversy is relatively straightforward. If you perform computer experiments badly, or leap to naive conclusions by forgetting the things that computer pictures do not show, then you can come up with nonsense. But dealing with such problems is part of any experimentalist's technique and experience. Most mathematicians are perfectly happy with the use of computers as tools for suggesting interesting theorems. They accept that experiments aren't proofs; but they find them useful nonetheless. They neither reject the computer, nor do they believe everything that it tells them. In mathematics, as in the rest of science, theory and experiment can go hand in hand.

[27]Moscow State University, Russia

The word 'symplectic' was coined by Hermann Weyl in his treatise *The Classical Groups*. In a footnote he says that it derives from the Greek for 'complex'. Weyl's book is about the groups of rigid motions of various basic kinds of multidimensional geometry. For ordinary Euclidean geometry, the rigid motions form the orthogonal group. Weyl devoted very little space to the symplectic group – it was then a rather baffling oddity which presumably existed for some purpose, though it wasn't clear what. Now we know: the purpose is dynamics.

In ordinary Euclidean geometry the central concept is distance. To capture the notion of distance algebraically we use the inner (or scalar) product $x.y$ of two vectors x and y. If $x = (x_1,x_2)$ and $y = (y_1,y_2)$ are vectors in the plane then

$$x.y = x_1y_1 + x_2y_2,$$

and a similar formula holds in higher dimensions. All the basic concepts of Euclidean geometry can be obtained from this inner product. In particular, a transformation T is a rigid motion if and only if it preserves the inner product, so that $Tx.Ty = x.y$.

Replacing the inner product by other similar algebraic expressions produces new kinds of geometry. Symplectic geometry corresponds to the form $x_1y_2 - x_2y_1$, which is the area of the parallelogram formed by the vectors x and y. Note the minus sign: it leaves footprints all over the symplectic landscape. This symplectic form provides the plane with a new kind of geometry, in which every vector has length zero and is at right angles to itself. There are analogues in spaces of any even number of dimensions.

Can such bizarre geometries be of practical relevance? Indeed they can: they are the geometries of classical mechanics. In Hamilton's formalism, mechanical systems are described by position coordinates $q_1,...,q_n$, momentum coordinates $p_1,...,p_n$, and a function H of these coordinates (nowadays called the Hamiltonian) which can be thought of as the total energy. Newton's equations of motion take the elegant form

$$\mathrm{d}q_i/\mathrm{d}t = \partial H/\partial p_i\ ,$$
$$\mathrm{d}p_i/\mathrm{d}t = -\partial H/\partial q_i\ .$$

When solving Hamilton's equations it is often useful to change coordinates. But if the position coordinates are transformed in some way, then the corresponding momenta must be transformed consistently. Pursuing this idea, we find that such transformations have to be the symplectic analogues of rigid Euclidean motions. The natural coordinate changes in dynamics are symplectic. This is a consequence of the asymmetry in Hamilton's equations, whereby $\mathrm{d}q/\mathrm{d}t$ is plus $\partial H/\partial p$, but $\mathrm{d}p/\mathrm{d}t$ is minus $\partial H/\partial q$. That minus sign again.

For symplectic *topology* we must be more flexible, and use transformations which 'in the small' look like symplectic rigid motions. We shall refer to them as symplectic mappings. In the plane the symplectic form represents area, so a symplectic rigid motion is a linear transformation that preserves area. To add flexibility, we relax the condition of linearity. A symplectic mapping of the plane is thus any transformation that preserves area. However shapes can change drastically. For a mental picture, think of the plane as an incompressible fluid and a symplectic mapping as something that stirs the fluid around. (This is not just a picture: fluid mechanics can fruitfully be recast in symplectic language.)

Differential topology is the study of smooth mappings of a manifold. Analogously, symplectic topology is the study of symplectic mappings of a symplectic manifold. The earliest theorem of symplectic topology, invented long before such a subject existed, is Henri Poincaré's last geometric theorem, arising from a problem in celestial mechanics. The theorem states that an area-preserving (that is, symplectic) transformation of an annulus (region between two circles), which moves the two boundary circles in opposite directions, has at least two fixed points. Such 'fixed point theorems' are very powerful: this one, proved by George Birkhoff in 1913, implies the existence of periodic orbits in the motion of three bodies under gravity. If the transformation is not symplectic, there need not be any fixed points; so symplectic topology has its own distinctive character. An important problem known as the Weinstein conjecture, about the existence of periodic trajectories, was proved by Claude Viterbo[28] in 1987. There are symplectic versions of knot theory, and many problems that are peculiar to the symplectic world.

The traditional applications of symplectic geometry are

[28]CNRS Paris, France

mechanics and optics. But perhaps the most important current application is to quantum field theory, where the language of symplectic geometry has shed a great deal of light upon the process of quantization – passing from a classical system to its quantum counterpart.

ALGORITHMS AND COMPLEXITY

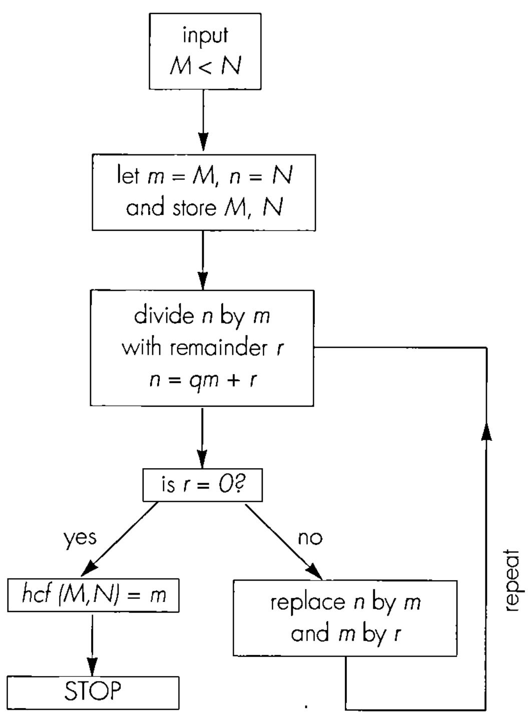
The computer scientist Donald Knuth once remarked that the main difference between mathematics and computer science is that mathematicians do not worry about the cost of a calculation. He did not mean cost in the monetary sense: he was referring to the amount of computational effort needed to get an answer. A rapidly growing new area of mathematics has made such concepts precise, and raised some absolutely fundamental questions about the nature of computation. It is known as complexity theory (or computational complexity theory to distinguish it from another area of science also called complexity theory, which tackles the emergence of order in very complicated systems).

Many common mathematical procedures provide answers in principle but not in practice. For example, we can test whether a number n is prime by trying all possible divisors up to $\sqrt{n}$. But this test is impractical for numbers of, say, 50 digits, for which it requires 10^{25} trial divisions. On a supercomputer that could carry out a billion such operations per second – rather faster than currently available – the test would run for about 300 million years. (Simple improvements can reduce this time a little: dividing only by odd numbers and 2 takes a mere 150 million years. But this improvement is more than wiped out if we seek to test a 52-digit number, which takes 10 times as long with either method.) It is, however, entirely practical to test numbers up to about 100-120 digits for primality – but not by trial division. Instead, clever number-theoretic methods must be used.

The object of attention in this area is not the answer to a mathematical problem, but the process – or algorithm – used to calculate that answer. Roughly speaking, an algorithm is a set of calculations that is guaranteed to give an answer. The process 'try factors at random until you find one' is not an algorithm for primality testing, because it could go on indefinitely without coming to any definite conclusion. A precise definition of the term 'algorithm' requires a formal definition of the computational process; but for present purposes it can be thought of as a computer program.

Most computational questions depend upon some input – a number or a more complicated set of data. The primality algorithm depends upon inputting the number n. We measure the size of the input by the number of binary digits (0 or 1) required to specify it, which here is roughly $\log_2 n$. What concerns us is how the running time of the algorithm – the number of computational steps – varies with the size of the input. This may appear to depend upon

FIGURE 4
THE EUCLIDEAN ALGORITHM



Flowchart for the Euclidean algorithm to find the highest common factor of two integers *m* and *n*.

the precise type of computational step – multiplications take much longer than additions, for example – but the most basic distinction is not affected by such considerations. This is not the precise running time, but the way in which it grows as the input data size becomes large.

What is the general order of magnitude of the running time of the impractical trial division algorithm? An input number with n binary digits will be of the order 2^n, so its square root is of the order $2^{n/2} = (\sqrt{2})^n$. This grows exponentially fast as n increases, which renders the algorithm impractical even for moderate sized n. In contrast, the standard Euclidean algorithm to find the greatest common divisor of two numbers (Figure 4) has a running time of the order $16n$ for input numbers with n binary digits. This is linear in n, so it grows far more slowly: inputs with a million digits require only 16 million calculations, taking less than a second on our hypothetical supercomputer.

Algorithms whose running time varies roughly as n^2, or n^3, or more generally as some fixed power of n, are also 'practical'. For theoretical purposes the crucial distinction is between algorithms whose running time is at most Kn^a, where K and a are constants, and those whose running time is more than Lb^n where L and b are constants. The former are said to run in *polynomial time* (or be of class P), and the latter run in *exponential time*. Sandwiched in between are algorithms whose running time is faster than polynomial but slower than exponential: the best known algorithms for primality testing are in fact of this type.

The core of complexity theory is how the running times of algorithms grow with the size of input data, which places limits on the possible efficiency of algorithms. The central difficulty is to prove that some problems inevitably lead to inefficient algorithms. The main difficulty is that if the best known algorithm for a problem runs in, say, exponential time, then we cannot conclude that *every* algorithm to solve the same problem also runs in exponential time. There may be an as yet unknown efficient algorithm that runs much more quickly.

A case in point is the travelling salesman problem, which first appeared in the United States in the 1930s, the early days of operational research. A salesman has to visit a number of cities and return to the starting point. The cities and the distances between them are given: what is the shortest route? As for primality testing, the obvious approach – exhaustive trial of all possibilities – is hopelessly inefficient. For n cities the number of tours is $(n-1)!$, which increases rather faster than exponentially.

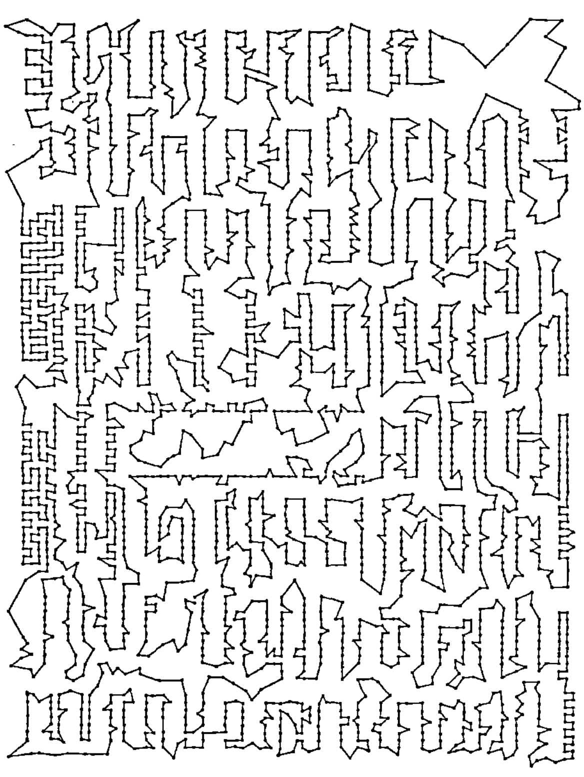
Does an efficient algorithm for the travelling salesman problem exist? In particular, is there one in the class P? Nobody has ever found one. Research on this kind of question is currently focused around a particular class of problems known as NP (non-deterministic polynomial time). Roughly speaking, these are problems for which there exists an efficient verification procedure for any claimed solution. For example, although it can take days to solve a complicated jigsaw puzzle, a single glance will verify that the solution is correct. The travelling salesman problem is in the class NP; but there is a huge conceptual gap between checking a solution efficiently and finding one efficiently. Think of a jigsaw puzzle. Indeed the biggest unsolved problem in the entire area is whether NP is different from P.

In 1971 Stephen Cook[29] found what looked like the most difficult NP problem. He showed that if a particular problem in mathematical logic, known to be of class NP, was actually of class P, then the same must hold for every other problem of class NP. In other words, if this one particular logic problem is in class P, then $NP = P$. (In particular, there would then have to be an efficient algorithm for the travelling salesman problem.) Such problems are said to be NP-complete. It has subsequently turned out, however, that this particular problem is not as special as it seems: virtually every NP problem that is not known to be in P is NP-complete – including the travelling salesman problem. The reason is that any one of these problems can be converted into a special case of any of the others in a manner that changes the running time in a polynomial way. If anyone can prove that the travelling salesman problem really is hard (not in P) then they will automatically prove that a huge number of other problems are also hard. But nobody even knows where to begin.

As a practical matter, quite large travelling salesman problems can be solved by special methods. The current record is 3 038 cities (Figure 5). But questions about the manufacture of computer chips (moving a laser to various

[29]University of Toronto, Canada

FIGURE 5
THE TRAVELLING SALESMAN PROBLEM



The currrent record for the travelling salesman problem – traversing 3 038 points on a printed circuit board.

positions in turn, to drill tiny holes) are equivalent to a travelling salesman problem on more than a million cities. In practice good approximations to the best solution, rather than the exact best, suffice; and efficient approximate algorithms have been found for many problems. However, in 1992 Sanjeev Arora[30], Madhu Sudan[31], Rajeev Motwani[32], Carsten Lund[33] and Mario Szegedy[34] proved that if $NP \neq P$, then there is a threshold size of input data beyond which approximations necessarily become bad.

Complexity theory is a promising area for development. The basic question whether $NP \neq P$ is very difficult; but there is much scope for the invention of new and more efficient algorithms – exact or approximate – for practical problems, new techniques for finding the running time of known algorithms, and so on. There are also important extensions. Lenore Blum[35], Michael Shub[36] and Stephen Smale[37] have developed a theory of computation over the real numbers that models techniques of numerical analysis. In their theory, calculations are considered to be carried out to infinite precision. One consequence is the verification of a conjecture by Roger Penrose[38] that the Mandelbrot set is uncomputable, in the sense that no algorithm using infinite precision real numbers can decide whether or not a given number belongs to that set. Complexity theory provides a rigorous proof that chaos is uncomputable.

THE SPECTRUM OF THE LAPLACE OPERATOR

Everything in the universe vibrates. The light that reaches us from the most distant galaxy and the sound of a nightingale are brought to us by vibrations – of the space-time continuum, and the atmosphere, respectively. The tone of a Stradivarius violin, and the stability of a car wheel, depend on how they vibrate. And each object has not just one, but a whole range of characteristic resonant frequencies of vibration, known as normal modes. Mathematically, small-amplitude vibrations of any medium are described by the wave equation. This was originally devised in the 18th century by Leonhard Euler in a study of musical instruments, but Joseph-Louis Lagrange extended it to sound waves, and further extensions soon followed. The wave equation became perhaps the most important of all the equations of mathematical physics. Its mathematical form is

$$\frac{d^2 f}{dt^2} = \Delta f$$

where the Laplace operator Δ is defined by

$$\Delta f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2}.$$

The characteristic frequencies of a vibrating shape correspond to the eigenvalues λ of the Laplacian, that is, the solutions of the equation $\Delta f + \lambda f = 0$. In this equation you should think of the boundary as being held fixed while the

[30,31]University of California at Berkeley, USA. [31]University of California at Berkeley, USA. [32]Stanford University, USA. [33,34]Bell Laboratories, USA. [35]International Computer Science Institute, Berkeley, USA. [36]IBM Thomas J. Watson Research Center, Yorktown Heights, USA. [37]University of California at Berkeley, USA. [38]University of Oxford, UK

rest of the shape vibrates, just as in a drum or a violin string.

The fundamental frequency of a violin is determined by the tension in the string. But it can also generate harmonics of the fundamental frequency – vibrations that occur twice as fast, or three times, or four times... . Here the pattern is easily described: the possible frequencies follow the series of whole numbers 1,2,3,... . But more complicated shapes produce more complicated series of frequencies. Hermann Weyl proved that provided they have smooth edges, all shapes vibrate in a sequence of frequencies

$$\lambda_1 \leq \lambda_2 \leq \lambda_3 \leq \ldots .$$

This sequence is called the spectrum of the shape.

In 1966 Mark Kac asked whether different shapes

CONTROVERSY OVER KEPLER

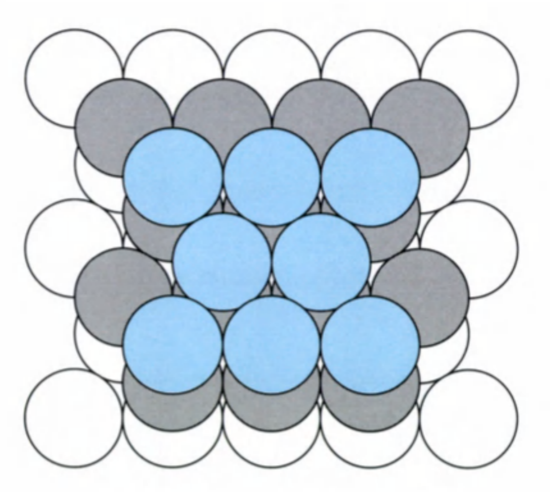
One of the oldest puzzles in mathematics is a problem that predates Fermat's Last Theorem by three decades. It is known as the Kepler Problem. It survived for nearly four centuries without a scratch, until in 1991 Wu-Yi Hsiang, University of California at Berkeley, USA, claimed a proof. However, the validity of his proof is currently in dispute.

Johannes Kepler is best known for his laws of planetary motion; but in a book written as a New Year's present for his sponsor he mused about snowflakes. Why do they have hexagonal symmetry? The question led him to some remarkable insights into crystal structure, three centuries before physicists started to develop the atomic theory of matter; and to the mathematical problem of packing identical spheres into the smallest possible space. He considered three particular packings, known to crystallographers as the cubic lattice, hexagonal lattice, and face-centred cubic lattice (see figure, right). Kepler asserts that 'the packing will be the tightest possible' for the face-centred cubic lattice. The Kepler Problem is to prove this – not just among the three types of packing, but for any packing whatsoever, regular or random. The density of the packing – the proportion of space occupied by the spheres – is $\pi/\sqrt{18}$, or about 74%.

Hsiang's proof is cast entirely in the classical language of spherical geometry, vectors and calculus, and in its first version it occupied 100 pages of tricky geometry. It has not yet been published, but is widely available in preprint form. It took about a year for the doubts to surface. John Horton Conway, Princeton University, USA, and Thomas Hales, University of Chicago, USA, were the first to make their scepticism public. They pointed out that Hsiang's original preprints contain several obvious errors. He has since corrected these, and streamlined the proof considerably; but many mathematicians are now chary about spending a lot of time trying to understand the new proof when the original was so flawed. Among those who have made the attempt is Jon Reed, University of Oslo, Norway, and he is convinced the proof is now correct. The best universally accepted result is that of Douglas Muder, Mitre Corporation, Bedford, Massachusetts, USA, who has proved that the density of any sphere-packing is at most 77.386%. Muder is still worried about what he calls 'unsupported claims' in Hsiang's attempted proof. He is willing to believe that it might be possible to justify them rigorously, but says that the existing proof fails to do so. Hsiang, on the other hand, believes it is just a matter of waiting for other people's geometric intuition to catch up with his own.

When complicated and lengthy proofs for difficult unsolved problems are first presented, it can take mathematicians quite a while to work through them, understand the main ideas, and get the feel of the proof. The more important the theorem, the more sceptical the mathematical community's initial reaction tends to be. Initial versions of complicated proofs nearly always contain errors: some can be fatal, others can be patched up. For the Kepler Problem, the jury is still out. The sociology of mathematical proof is almost as complicated as the logic.

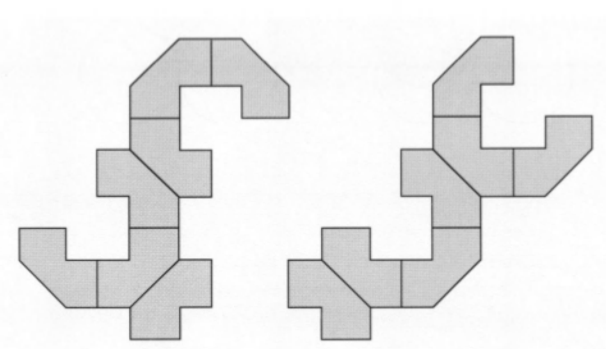
Three successive layers of the face-centred cubic lattice, widely conjectured to be the most efficient way to pack identical spheres in space.



necessarily have different spectra. As he put it, can you hear the shape of a drum? He showed that the area and perimeter of a drum – a two-dimensional shape in the plane – are determined by the drum's spectrum. (Weyl had already proved a theorem that implied the area is so determined, see below.) Over a quarter of a century later, his question has now been answered – negatively – by Carolyn Gordon[39], David Webb[40] and Scott Wolpert[41]. They have constructed two different drums (Figure 6) with identical spectra. Similar examples have been known in higher dimensions since 1964, when John Milnor[42] found two different 16-dimensional tori with the same spectra. In 1985 Toshikazu Sunada[43] found a general criterion for two shapes to have the same spectrum. Using it, Peter Buser[44], Robert Brooks[45] and Richard Tse[46] found two distinct curved surfaces (bells) in three-dimensional space with the same spectrum. The drums in the illustration are flattened versions of one of their examples.

FIGURE 6

TWO DIFFERENT DRUMS WITH THE SAME VIBRATIONAL SPECTRA



Among Hermann Weyl's early achievements is a proof that the spectrum of a manifold always determines its multidimensional 'volume'. He did this by proving a formula describing the asymptotic properties of the vibrations at high frequency. Specifically, let $N(\lambda)$ be the number of characteristic frequencies less than a given value λ. He showed that $N(\lambda)$ is asymptotic to $k\lambda^{n/2}$, where n is the dimension of the vibrating object and the constant k depends on its volume. Here the term 'asymptotic' means that the ratio of the true answer to that given by Weyl's formula tends to 1 as λ tends to infinity. But that gives only very coarse information. To improve Weyl's formula we must ask how large the error can become. In 1980 Michael Berry[47] conjectured, on physical grounds, that a more accurate version of Weyl's results should be true, and that it should apply not just to the smooth shapes envisaged by Weyl, but to shapes with fractal boundaries.

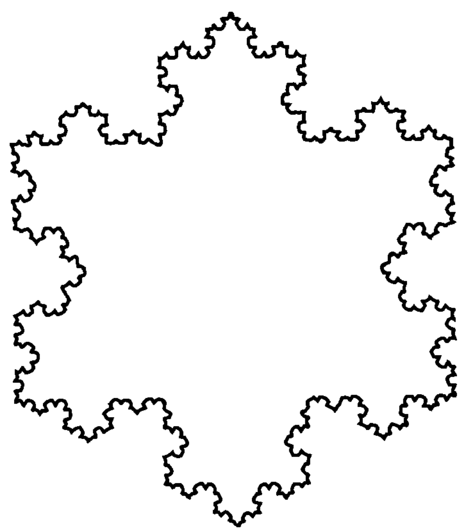
Recall that a fractal is a shape with detailed structure on all scales of magnification. Many natural objects are better modelled by fractals than by smooth surfaces, and vibrations of fractal objects are important. Examples include the vibrations of water in a lake with an irregular edge; seismic oscillations of the entire Earth; and the acoustic properties of a concert hall with irregularly shaped walls. The archetypal fractal is the snowflake curve (Figure 7). Begin with an equilateral triangle. To each edge add an equilateral triangle one third the size. Now repeat indefinitely, adding ever-smaller triangles. How does a drum shaped like a snowflake vibrate? According to Berry, much like a drum with a smooth rim, until you look at the fine detail, the high-frequency vibrations that penetrate into tiny crevices of the boundary. Here, more vibrations should be possible, because fractal objects have lots of ever-smaller crevices. So the number $N(\lambda)$ should be bigger. Berry gave arguments to suggest that the error should be about $\lambda^{d/2}$ where d is the dimension of the boundary of the snowflake.

What do we mean by the dimension of the boundary, when the boundary is an irregular fractal? Berry's conjecture was that it should be the fractal dimension, or Hausdorff-Besicovitch dimension. This concept, which is fundamental to the analysis of fractals, measures their behaviour under changes of scale. In particular it need not be a whole number, unlike the more usual concept of dimension. For the snowflake d is about 1.2618. So the error in Weyl's formula should be of the order of magnitude of $\lambda^{0.6309}$, compared to $\lambda^{0.5}$ for a drum with a smooth rim.

The first point to make about Berry's conjecture is that it is false. This was shown by Jean Brossard[48] and René Carmona[49] in 1986. That might seem to be the end of the story, except that the physical intuition behind the

[39,40]Dartmouth College, USA. [41]University of Maryland, USA. [42]Institute for Advanced Study, Princeton, USA. [43]Nagoya University, Japan. [44]Ecole Polytechnique, Lausanne, Switzerland, [45]University of Southern California, USA. [46]*Affiliation not known.* [47]University of Bristol, UK. [48]University of Grenoble, France. [49]University of California, Irvine, USA

FIGURE 7
THE SNOWFLAKE CURVE



Source Peitgen H-O., Jürgens, H. and Saupe, D. (1993) *Chaos and Fractals. New Frontiers of Science*, New York, Springer-Verlag 99, Figure 2.29

conjecture still looks very appealing. Michael Lapidus[50] and Jacqueline Fleckinger-Pellé[51] have shown that the conjecture can be put right, if the Hausdorff-Besicovich dimension is replaced by the less familiar 'Minkowski dimension'.

The importance of physical intuition for mathematical discovery is clear, and this important extension of Weyl's classic result is an excellent case in point. But it teaches other lessons too. One is the need for proper mathematical rigour, without which it would not have been realized that the most popular definition of fractal dimension is not the appropriate one here. The second is that, while intuition can suggest that certain results are true, it does not always suggest the correct line of attack for a proof – which here required classical analytic methods. And a third is that relatively neglected ideas from pure mathematics – here Minkowski's version of dimension – can suddenly spring to life in new applications.

Mathematics needs science, and science needs mathematics.

IAN STEWART is a Professor in the Mathematics Institute at the University of Warwick, United Kingdom, and has held visiting positions in Germany, New Zealand and the USA. He is the author of several books on mathematics and writes the 'Mathematical Recreations' column in *Scientific American*. His current research is on the effects of symmetry on dynamics, with applications to pattern formation, animal locomotion and chaos.

Professor Stewart obtained a BA at Cambridge University and a PhD at the University of Warwick.

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[50]University of Georgia, Athens, USA. [51]University of Toulouse-I, France

PHYSICS

Phillip F. Schewe

The clearest perspective of recent progress in physics is perhaps achieved when new additions to knowledge are reviewed over a vast range of distance scales, starting with quarks – thought to be the smallest (perhaps even pointlike) and most elementary of all the particles – and continuing with objects of increasingly large size such as nuclei, atoms, solids, planets, galaxies, and ending with the universe as a whole.

On the theoretical front, much effort has been given to unifying strands of knowledge, whether on the small scale typical of interactions among subatomic particles or on the immensely larger scale where galaxies form and collide.

On the experimental front, an ever-improving arsenal of lasers, microscopes, atom traps, accelerators and telescopes has allowed us to sample nature over an unprecedented spectrum of temperatures (from trillionths to trillions of degrees), wavelengths (long radio waves from the edge of the solar system to extremely short gamma rays from the centre of our galaxy) and times (Z particles decay in 10^{-24} seconds, but cosmic microwaves take 15 billion years to get to Earth).

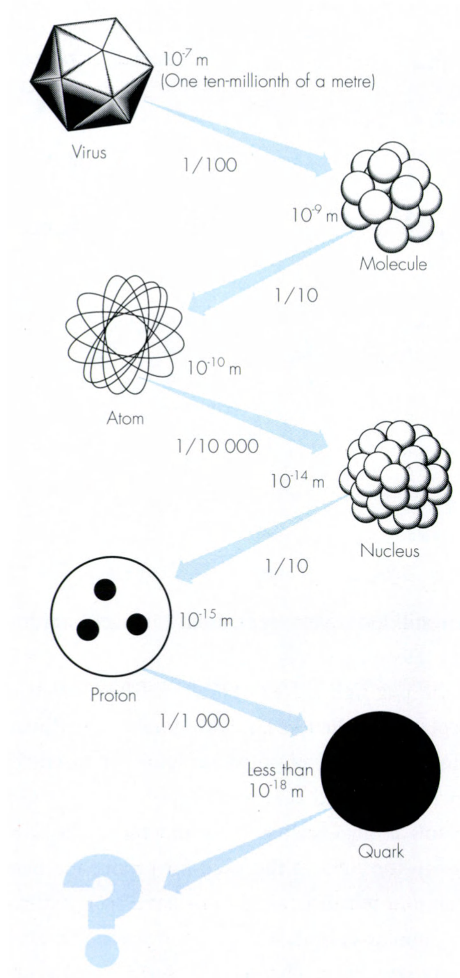
THE STANDARD MODEL OF PARTICLE PHYSICS

What are the elementary constituents of matter? Some early Greeks thought that the building blocks of nature were 'atoms'. Medieval thinkers felt that all matter was made from four elements: fire, air, water and earth. In recent centuries the idea of atoms as the basic unit of matter was revived as more and more chemical elements were discovered. In the 19th century, patterns in the properties of the elements became apparent and were codified in the form of the Periodic Table.

Then in 1911, Ernest Rutherford demonstrated that atoms themselves have constituents, namely a heavy nuclear core surrounded by electrons. He did this by shooting alpha particles at a thin gold foil. Only if the gold atoms had a heavy nucleus would the alpha particles scatter in the way that they did. Later it was found that the nucleus itself is made up of neutrons and protons. Even these particles, thought to be elementary as late as the 1960s, are now known to have constituents called quarks.

An overall view of particle physics, including a description of the known physical forces and a consensus of opinion on what constitutes an elementary particle, has been emerging over the past 20 years or so. Called the standard model, this theoretical framework suggests that there exist two main elementary particle families, the quarks – which come in six types, or 'flavours': up, down, strange, charm, top and bottom – and leptons – which also come in six flavours: electron, electron neutrino, muon,

FIGURE 1
THE STRUCTURE OF MATTER, WITH CHARACTERISTIC SIZES GIVEN IN METRES



muon neutrino, tau and tau neutrino. The standard model holds that all other particles are made from these most fundamental particles. Leptons can be detected and studied directly in the laboratory, but quarks never appear singly, only in groups (bound states) of two, called mesons (such as the pion or kaon), or in groups of three, called baryons (examples include protons and neutrons). Particles in general are further divided into two broad categories: fermions, particles possessing a half-integral spin, and bosons, possessing an integral spin (0 or 1 or 2, etc.).

One other important precept of the standard model is that all particles interact via four forces, each of which is carried by a special 'gauge boson' (the name gauge being a vestige of earlier theories):

the strong force, carried by gluons, acts only inside the nucleus, serving to hold it together;

the weak force, carried by the Z^0, W^+, and W^- particles, also operates inside the nucleus, but is much weaker than the strong force, and is responsible for certain types of radioactive decays;

the electromagnetic force, carried by photons, holds atoms together and is responsible for all electric and magnetic phenomena, and chemical reactions;

gravity, embodied in particle form as gravitons, is the weakest of the four forces but potent nevertheless over the large distance and mass scale of the cosmos.

Within the standard model are several specific theories, called gauge theories, that encapsulate the idea of forces being carried by gauge bosons. One of them is quantum electrodynamics (QED), the theory of the electromagnetic force. QED makes many highly precise predictions about a wide variety of electromagnetic phenomena, particularly at the atomic scale, and numerous experiments have upheld its validity. The electroweak theory combines the electromagnetic and weak forces into a single mathematical framework. These two forces evidently have very different properties at the present time but it is thought that in an earlier and colder time in the universe they constituted two manifestations of the same underlying force. A third theory, quantum chromodynamics (QCD), describes the strong force. Particles (whether mesons or baryons) that interact via the strong force are called hadrons. In QCD, quarks are said to possess a special charge, called colour charge (in analogy to electrical charge); the strong force between quarks is therefore sometimes referred to as the colour force, whence the name chromodynamics. Yet another theory, the grand unified theory (somewhat misnamed since it omits gravity), seeks to unify the strong and electroweak forces.

All of these theories must be tested in experiments. Because the investigation of properties of particles and the search for new forces are usually carried out by colliding particles together at high energies, the study of particle physics is often called high-energy physics. Indeed the accelerators which propel beams of particles to velocities close to the speed of light can be compared to giant microscopes illuminating matter at the smallest scale possible. As the acceleration energy goes up, the 'resolving power', the ability to probe matter in fine detail, also increases.

For this reason much of the nomenclature used in particle physics derives from the need to accelerate particles to high energies. For example, the electron volt (eV), defined as the energy gained by an electron accelerated through a potential difference of one volt, has become the standard unit of energy. Accelerators now commonly produce beams with energies of billions of electron volts (giga-electron volts, or GeV) or even trillions of electron volts (tera-electron volts, or TeV). Even masses are expressed in units of eV: the proton is said to have a mass of 0.938 GeV/c^2, where c is the speed of light.

PROTON-ANTIPROTON EXPERIMENTS

To probe matter at smaller distance scales, scientists need ever-higher energies; larger and more expensive 'microscopes' are needed. The highest energy machines are accelerators in which two beams of protons collide head-on. At the Superconducting Super Collider (SSC), under construction near Dallas, Texas, two separate proton beams will race around an 83-km track and collide at several designated interaction areas with a total energy of 40 TeV. The estimated completion date for this US$11 billion project is sometime shortly after the turn of the century.

The other large proton-proton collider under consideration is the Large Hadron Collider (LHC), which would use the same 27-km underground tunnel now occupied by the Large Electron-Positron (LEP) collider at the European Centre for Nuclear Research (CERN) laboratory in Geneva, Switzerland. The LHC project, not yet fully approved by the multinational CERN Council, would have a total energy – 16 TeV – somewhat smaller than SSC's, but both machines would have comparable goals: the study of matter at small distance scales – perhaps as small as 10^{-18} metres – and the search for new particles, such as the hypothetical Higgs boson.

Meanwhile, the 7-km Tevatron at the Fermi National Accelerator Laboratory (or Fermilab for short) near Chicago, Illinois, currently produces the largest collision energy of any existing accelerator. Beams of protons and antiprotons are collided there with a total energy of 1.8 TeV. In addition to producing beams for colliding head on, the Tevatron also produces beams that can be smashed into stationary targets. These beams may consist of protons or various secondary particles such as mesons and neutrinos.

Perhaps the most important objective at Fermilab right now is the search for the top quark. (See Figure B, colour section p. ii.) The top is the only one of the six quark types prescribed by the standard model that has not yet been observed in laboratory experiments. Recent reports from the CDF (Collider Detector at Fermilab) collaboration preclude a top quark mass less than 108 GeV. A comparable value, 103 GeV, has been reported for the D0 detector. Both of the mammoth detectors (each employing more than 400 physicists and the efforts of many nations) have recorded a small number of events (officially two for CDF and one for D0) suggestive of top-quark production, events in which a high-energy muon or electron, along with jets of other particles, emerges from the proton-antiproton collision. The Tevatron scientists admit, however, that such events might also be ascribed to a variety of non-top background reactions.

Fermilab director John Peoples has said that an inventory of at least 10 events in each detector would be necessary before one could even consider declaring that the top had been produced unambiguously. This underscores the statistical nature of the search for the top: the Tevatron has more than enough energy to create quarks with masses of 200 GeV or more, but the basic probability of this happening in any one interaction is extremely small. What is needed is much more data, and an important way of providing that is to increase the luminosity, the rate at which beam particles can be brought to bear at the interaction point. After a scheduled shutdown (June-October 1993) the Tevatron is expected to operate with a larger luminosity and at a higher energy, 2 TeV.

ELECTRON-POSITRON EXPERIMENTS

The SSC, LHC and the Tevatron use beams of protons or antiprotons, which are composite objects containing quarks. For certain types of experiments it is preferable to use beams of electrons or positrons, which are, as theorists believe, truly pointlike. For example, the Z boson, one of the carriers of the weak force, was first detected in the early 1980s at CERN in a proton-antiproton collider. But since then the study of this particle has been carried out mainly in the province of electron-positron colliders, where Zs are produced (in large numbers if the collision energy is just right) out of the miniature fireball created when an electron and positron collide and annihilate each other.

Indeed, more than a million Zs have been recorded in the four detectors at LEP and a much smaller number at the Stanford Linear Collider (SLC) at the Stanford Linear Accelerator Center (SLAC) in California. LEP and SLC both feature a collision energy of 100 GeV. But while LEP is a conventional storage accelerator, with electron and positron beams travelling millions of times around a ring of magnets, the particles at SLC race down a 3-km-long linear acceleration channel, are directed (electrons in one direction and positrons in the other) around short semicircular arms, and then collide once in a detector area and are not recirculated further.

Properties of the Z boson

Experiments at SLC and LEP chiefly study the properties of the Z boson and various aspects of the electroweak force. Consider a graph of the number of annihilation events observed as a function of the collision energy. A bump in the plot around an energy of 91 GeV corresponds to the resonant production of Z bosons; that is, although the Z does not ordinarily exist as a free particle, nature has contrived that the energy liberated, when an electron and positron annihilate at a collision energy of 91 GeV, should manifest itself in the form of a Z. The Z does not live very long before decaying, but scientists can still learn a lot about it. For instance, the centre of the bump on the graph occurs at a value equal to the mass of the Z. A current LEP measurement gives a value of 91.187 (with an uncertainty of 0.007) GeV/c^2.

The width of the bump is also important. The Heisenberg uncertainty principle prescribes that the width of the Z resonance peak is inversely proportional to the Z lifetime, which in turn depends on the number of decay possibilities available. The more types, or 'generations', of elementary particles there are (at least generations of particles which have masses less than half that of the Z), the shorter will be the Z lifetime, and the greater the width. The standard model currently accommodates three generations – electron, mu and tau – but does not explicitly exclude the possibility of others. It has been calculated that each generation contributes approximately 160 MeV to the Z width, so an accurate measurement of the width would provide a likely number of particle generations. Experiments at LEP and SLC, and even at the Tevatron, suggest that the total number of particle generations is precisely the three we know about already. Determining that this is so was not only important for particle physicists but also for cosmologists who are attempting to work out the dynamics of the early universe.

It is interesting to note that lunar tidal effects are the main cause of error in determining the mass of the Z boson. Scientists at CERN, with help from workers at SLAC and the University of Lausanne, have found that the

EXPERIMENTS WITH TRAPPED ATOMS

A whole class of atomic physics experiments depends on the ability to trap and study small numbers of atoms and molecules. The trapping device usually employs a set of lasers, sometimes referred to as 'optical molasses' to slow atoms and, sometimes with the additional help of electrostatic or magnetic fields, to fix them neatly in place. The 'temperature' of a small sample of such slow atoms would be extremely low. For example, Steven Chu and his colleagues at Stanford University, USA, cool a sample of sodium atoms and then push them upwards (using another laser) into a cavity where a further selection of atoms by velocity could be accomplished. In this way, a secondary beam of atoms with a velocity spread (in one dimension) of only 270 microns per second – or an equivalent 'one-dimensional temperature' of 24 picokelvins – was created.

New measurements of atomic masses with 20 to 1 000 times the precision of previous values have been made by David Pritchard's team at MIT. (See Figure C, colour section p. ii.) Masses of hydrogen, deuterium, oxygen, neon and argon have been measured at precision levels of around 100 parts per trillion. The researchers made their measurements using a Penning trap, a device in which an isolated ion's cyclotron motion in a magnetic field is compared to that of a reference ion. The ratio of the cyclotron frequencies determines their relative masses. These are then converted to a scale based on the carbon-12 mass. The MIT scientists have also mentioned that they hoped to 'weigh' the binding energies of chemical bonds; but this requires a tenfold improvement in precision. Pritchard believes an improvement of this magnitude entails the development of a technique in which the two ions occupy the Penning trap simultaneously. Robert Van Dyck of the University of Washington has reported that Penning trap measurements of the mass difference between helium-3 and tritium give a value of 18 590.1 eV with an uncertainty of 1.7 eV. This measurement provides a systematic check of tritium beta decay experiments investigating the possibility of a non-zero neutrino mass.

A new version of Young's interference experiment, using not a pair of slits in a screen but instead a pair of mercury ions in an atom trap to scatter light waves and produce interference fringes, has been performed by Ulli Eichmann's group at the National Institute of Standards and Technology in Boulder, Colorado. The researchers used a single laser beam both to cool (to microkelvin temperatures) the ions, which are held in the inhomogeneous electric fields of an atom trap, and to serve as a light source for producing interference effects. Stable fringe patterns were produced for several relative spacings (typically a few microns) for the ions. The fringe pattern, in turn, may be used as a diagnostic for measuring the temperature or spacing of ions in various trap experiments.

Moon's gravitational pull warps the shape of the LEP collider by as much as a millimetre (out of a total circumference of 27 km). This blurs the Z mass estimates by about 10 MeV. Hereafter, calibrations of the beam energy will take into account the phase of the Moon.

The Grand Unified Theory

Other experiments at LEP examine the nature of the Grand Unified Theory (GUT) of particle physics. GUT predicts that at very high energies (10^{15} GeV), corresponding to the conditions that prevailed at very early times after the Big Bang, the electromagnetic, weak and strong forces should be comparable in strength. At the lower energies available at particle accelerators, the relative strengths of the forces are expressed as three 'coupling constants'. Using data from LEP, scientists have extrapolated the value of the 'coupling constants' up into the energy range at which unification would take place. The failure of the three curves to intersect in a single point has been interpreted by some as evidence that new physical effects, not accounted for by the so-called standard model, may be at work.

The 'supersymmetry' model

One explanation for this behaviour is provided by the 'supersymmetry' model, a theory based on a supposed symmetry (relationship) between fermions and bosons. This theory predicts, for example, that bosons, such as photons and gluons, have fermion counterparts (in this case photoninos and gluinos) and that fermions, such as leptons and quarks, would have boson counterparts (in this case called sleptons and squarks). One of the goals of this theory is to unite all the physical forces into a single framework, including gravity. While accelerators like LEP or the Tevatron hope to see such supersymmetric particles directly in the laboratory, LEP's extrapolated values for the coupling constants provide at least some indirect information about supersymmetry.

The SLC produces far fewer Zs than LEP, but it has been able partially to polarize its electron beam. A polarized beam is one for which some of the electrons have been specially oriented so that their spins lie either along or against the direction of motion. Such polarized electrons are referred to as being right-handed or left-handed. It turns out that the electroweak force is sensitive to the polarization and that therefore there should exist a left-right asymmetry in the production of Zs. That is, the rate of Z production should be different for left- and right-handed electrons. Such an asymmetry has been observed in the SLC experiments.

The left-right asymmetry can be used to measure the Weinberg angle (or, more precisely, the square of the sine of the Weinberg angle), a factor named after the University of Texas physicist Steven Weinberg that describes the relative importance of Z bosons and photons in the theory of the electroweak force. SLC's new value for this factor, 0.2378, is comparable in precision to measurements made in other interaction experiments. However, as the SLC work continues and as the level of polarization increases (polarizations of greater than 50% have been achieved so far) the precision of their Weinberg angle measurement will also improve.

Probing the proton's inner structure

The experiments described so far have involved either proton-antiproton or electron-positron interactions. Another important class of interaction is that between electrons (or other leptons such as muons or neutrinos) and protons. Leptons, because they do not feel the nuclear force, serve as excellent probes of the proton's inner structure; they are able to penetrate deep inside the proton, often so deep that they scatter not from the proton as a whole, but from one of its constituent quarks. One such experiment has been carried out by the Spin Muon Collaboration (SMC) at CERN. An interesting result of their experiment, in which polarized muons were scattered from polarized deuterons (isotopes of hydrogen consisting of a proton and neutron bound together), is the determination that very little (less than 12%) of the spin of a proton or neutron comes from the spins of its constituent quarks.

A comparable experiment done at SLAC (the E142 collaboration) using polarized electrons scattering from a stationary target of polarized helium-3 atoms, has arrived at a very different determination, namely that the constituent quarks carry as much as 60% or more of the nucleon spin. Both the SLAC and CERN groups plan more extensive measurements to test this important issue.

The highest-energy lepton-proton scattering occurs at the Hadron-Electron Ring Accelerator (HERA) in Hamburg, Germany, where 30-GeV electrons collide with 820-GeV protons. (See Figure D, colour section p. iii.) Two parameters, the total centre-of-mass energy and the momentum transfer, will be at least a factor of 10 higher at HERA than at other accelerators, which must depend on fixed-target experiments for exploring lepton-hadron collisions. Larger momentum transfers allow scientists to probe the distribution of matter inside protons down to very small distance scales, in HERA's case down to 10^{-18} cm, 10 000 times smaller than the size of the proton. HERA has been performing physics experiments only since late 1992 and its scientists are at this time still trying to boost running conditions up to their optimum values.

NUCLEAR PHYSICS

Leptons and quarks are thought to be pointlike; protons and neutrons are made of quarks. The next larger arrangement of matter is the nucleus. One can sometimes study nuclei by passively observing their radioactive decays, but to excite nuclei to new exotic states takes energies of millions or billions of electron volts. Therefore nuclear physicists, like particle physicists, resort to the use of accelerators.

One new form of nuclear matter studied in recent years are superheavy elements above atomic number 106. Heavy elements just below these in the Periodic Table had been made by bombarding lighter elements with neutrons or alpha particles. But this approach did not work for synthesizing elements above 106 because of the inherent instability of such superheavy nuclei. Instead, scientists at the Institute for Heavy-Ion Research (GSI) in Darmstadt, Germany, had to use gentler techniques. They did employ accelerated beams of heavy ions, but used relatively modest energies so that a projectile nucleus would successfully 'fuse' with a target nucleus (of nearly the same nuclear weight) so as to create a heavy composite nucleus, one whose existence and properties could be inferred from the detection of a sequence of decay products such as alpha particles and lighter daughter nuclei. The fruits of this work were the discovery of the elements 107, 108 and 109, which recently received their official names: Nielborhium, Hessium and Meitnerium, named for Niels Bohr, the German state of Hessen and Lise Meitner, respectively.

The advent of beams of heavy ions with all or nearly all of their electrons removed allows scientists to study a variety of nuclear phenomena. For example, researchers at GSI have recently observed the first instance of bound-state beta decay. In ordinary beta decay a nucleus transforms itself by essentially turning one of its neutrons into a proton; this process is accompanied by the emission of two particles, an electron and an antineutrino, which escape from the decaying nucleus. But in the GSI experiment something different happened: the emitted electron became bound in the daughter atom. Bound-state beta decay, as this process is called, was first predicted in 1947. The GSI scientists observed the decay in completely ionized (+66) dysprosium atoms circulating in a storage ring. Although neutral dysprosium is stable, in a fully stripped form it decays via bound-state beta decay into highly ionized (+66) holmium (atomic number 67) with a half-life of 47 days, a value derived from the measured storage time of the holmium daughter ions. The GSI scientists report that bound-state beta decay is of minor importance for neutral atoms but might be the predominant decay mode for highly ionized atoms, such as those inside stellar plasmas during nucleosynthesis. Studies of these decays (which are accompanied by an essentially mono-energetic antineutrino) may also lead to more precise bounds on the mass of the antineutrino.

Measuring the S factor

Another recent nuclear physics experiment has implications for astronomers. The rate of helium burning in massive stars, particularly the ratio of two reactions – three helium nuclei fusing to form carbon-12 and helium and carbon fusing to form oxygen-16 – determines the sequence by which heavy elements build up in stellar cores and the fateful chronology by which massive stars approach a supernova condition. The rate at which oxygen is produced, the so-called S factor, has now been measured in two separate experiments (the carbon production rate had been previously measured), one at Yale University in Connecticut and the other at the Triumph accelerator in Vancouver, British Columbia. In both experiments scientists studied the decay of oxygen-16 into carbon and helium. It was necessary to measure this reverse reaction because the fusion rate for carbon and helium, at least under laboratory conditions on Earth, was prohibitively small. The two experimental results were rather similar and largely in agreement with theoretical calculations.

Superdeformed nuclei, nuclei that are oblate or stretched out and quickly rotating as a result of high-energy collisions, represent another exotic form of nuclear matter. These nuclei often de-excite themselves by flinging out a sequence of high-energy (gamma-ray) photons. Scientists at a number of laboratories[1] have in recent years observed that the sequence (or band) of gamma rays emitted by superdeformed dysprosium-152 and terbium-151 are surprisingly like the pattern observed for nuclei (such as mercury) in the atomic mass range of 190. Band twinning is the name for this curious similarity in the energy spectra. According to Marie-Anne Deleplanque[2], 'There is no explanation for any of these properties based on our present knowledge of nuclear structure.'

Nuclei with halos

The lithium-11 nucleus consists of nine nucleons surrounded at some distance by a pair of neutrons constituting a weakly bound halo. The existence of the halo was first suspected when, five years ago, nuclear scattering experiments showed that the reaction probability for Li-11 was significantly larger than expected; this suggested that the nuclear size was larger than normal. A new experiment has now actually measured the size of the halo in the act of breaking up. At the National Superconducting Cyclotron Laboratory at Michigan State University (MSU), a beam of radioactive Li-11 is created by sending oxygen-18 ions into a thin lithium foil. The Li-11 is then scattered from a target of lead nuclei, whose electric fields cause the relatively gentle break-up of the Li-11 into Li-9 and a pair of neutrons. When Li-11 is scattered instead from light nuclei, such as beryllium-9, fragmentation occurs through the agency of the strong nuclear force. Both types of scattering suggest that the Li-11 halo is five times larger than the size of the Li-9 nucleus. Since the halo represents a sort of 'neutron matter', experiments at MSU and several other labs, such as GANIL and Saclay in France and RIKEN in Japan, hope to examine the interactions between the halo neutrons and to seek out other nuclei with halos.

Quark-gluon plasma

Perhaps the most exotic form of nuclear matter being sought by scientists in accelerator experiments is called quark-gluon plasma, a hypothetical state in which the constituent quarks and gluons confined inside the protons and neutrons within nuclei would all spill together under the conditions of high temperature and high pressure brought about in high-energy collisions. At the highest energies employed so far, the heaviest nuclei used have been sulphur (atomic weight of 32), whereas for the heaviest nuclei used to date, the highest energies have been about 1 GeV per nucleon. This has not been enough to achieve quark-gluon plasma, so nuclear physicists are planning bigger experiments, using heavier nuclei – which provide more potential plasma particles than light nuclei – and higher energies.

At CERN's SPS collider (where the Z and W particles were discovered in the early 1980s) lead ions will be accelerated (probably in 1994) up to energies of 180 GeV per nucleon. The Relativistic Heavy Ion Collider (RHIC), under construction at Brookhaven National Laboratory in New York should (by 1997) be able to collide gold ions in interactions with total energies (eventually) as great as 40 TeV. Interactions under these extreme conditions should spawn as many as 10 000 charged particles per event, a larger multiplicity than will occur in a typical collision at the SSC collider.

ATOMIC AND MOLECULAR PHYSICS

After quarks, protons and nuclei, atoms are the next biggest agglomeration of matter in the universe. The study of atoms and molecules has been greatly aided by the versatility, tunability, high energy and narrow-energy spectrum of lasers. The use of beams of neutral atoms has also been important. For instance, manipulating beams of atoms with techniques normally used for beams of light is becoming more common. The high electric fields available in intense laser light and the advent of submicron machining have facilitated the development of a variety of atom beam splitters, lenses, mirrors and interferometers. One example: a laser beam, channeled through a dielectric

[1]including the Lawrence Berkeley Laboratory, California, USA, Argonne National Laboratory near Chicago, USA, Daresbury Laboratory, UK, Chalk River, Canada and Oak Ridge National Laboratory, Tennessee, USA. [2]Lawrence Berkeley Laboratory, California, USA

medium by total internal reflection, will exhibit an evanescent field, an exponentially-decaying light field in the vacuum just outside the medium. This light has been used to reflect neutral atoms. According to Martin Sigel and Jurgen Mlynek[3], if this or other atom mirror designs could be employed to make a cavity for containing standing or travelling atom waves, then it might be possible to store cold atoms or even to produce coherent atom beams.

Atom interferometry

Atom optics have also been used by scientists[4] to demonstrate atom interferometry. Interferometry is a phenomenon in which waves (light waves from a laser, for example) are split and made to interfere with themselves, resulting in a characteristic pattern of constructive and destructive interference. Previously, electrons and neutrons – which according to quantum mechanics have wavelike properties – have been subjected to interferometry. Now this process has been extended to atoms. David E. Pritchard[5] causes a highly collimated beam of sodium atoms with a de Broglie wavelength (the wavelength of sodium 'matter waves') of 0.16 angstroms (1 $Å=10^{-10}$ m) to pass through three sets of diffraction gratings, the first two to establish an interference pattern and the third to sample the pattern.

In another experiment, O. Carnal and J. Mlynek[6] cause a beam of atomic helium with a de Broglie wavelength of 0.56–1.03 Å to pass through a system of slits, creating an interference pattern at a detection plane 64 cm away. Atom interferometry will permit certain new studies of quantum mechanics and may be useful in testing general relativity. Extremely sensitive measurements of rotation – with possible applications in inertial guidance systems – may be possible.

NOBEL PRIZES

Pierre-Gilles de Gennes of the Collège de France in Paris was awarded the 1991 Nobel Prize in Physics for 'discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers'. De Gennes is widely known among physicists for his ability to bring clarity and rigour to the study of complicated physical systems and for his efforts to foster interdisciplinary ties between disparate fields.

In particular, de Gennes' accomplishments include the following. He was instrumental in putting polymer physics on a more mathematical footing. For example, he derived dimensionless parameters incorporating certain polymer properties – such as polymer length, molecular weight and radius of gyration – which obey scaling laws; that is, the parameters characterize the polymer conformation and behaviour over a wide range of experimental conditions, such as temperature or polymer concentration.

He formulated a theory which describes 'reptation', the movement (through the surrounding medium) of polymers along the direction of their longitudinal axis. Indeed, de Gennes' work provided what some scientists believe is the basis for an understanding of polymer viscosity and elasticity at the molecular level.

He has been a pioneer in the study of polymers at interfaces, a subject with practical applications in a variety of areas, such as turbulence suppression, lubrication, oil recovery, immunology and waste treatment.

The Nobel Prize in Physics for 1992 was awarded to **Georges Charpak** for his numerous contributions to the instrumentation used in experiments at high-energy accelerators. Many of the new particles discovered in the past few decades have used detectors developed or greatly improved by Charpak. In particular, his development of the multiwire proportional chamber – a sort of extension of the Geiger counter principle – in the 1960s allowed the trajectories of particles issuing from high-energy collisions to be tracked over distances of several metres or more with a spatial precision of less than 1 millimetre. Furthermore, the rate at which the chamber could make a measurement, recover, and then be able to make a new measurement, grew to be many thousands per second.

These characteristics of Charpak's detector – high spatial resolution and high repetition rate – were important in the study of rare interactions or the creation of short-lived exotic particles. Such experiments often necessitate the use of intense beams and the sampling of a large number of events in a short period of time. Indeed, Charpak's work helped to pave the way for a greater integration of computers into the data acquisition process. Charpak, a French citizen, has spent much of his career at the CERN laboratory in Geneva.

[3]University of Konstanz, Germany. [4]at Massachussetts Institute of Technology and Stanford University, USA, and University of Konstanz and University of Braunschweig, Germany. [5]Massachussetts Institute of Technology, USA. [6]University of Konstanz, Germany

Steven Chu[7] believes, for example, that local gravitation will be measurable to within one part in 10^{10} or even 10^{12}.

Atomic physicists would naturally like to study anti-atoms. The first step in making antihydrogen, creating positrons and antiprotons, is difficult enough, but forming a stable anti-atom out of the antiparticles seems harder still. Gerald Gabrielse[8] uses the Low Energy Antiproton Ring (LEAR) at CERN plus his own electrostatic atom trap to slow (and store) antiprotons down to energies as low as 0.3 meV. Bringing them together with positrons (perhaps in a double-trap setup) is several years off. At Fermilab, Charles Munger of SLAC hopes to search for the very few antihydrogen atoms he suspects may be generated when a beam of antiprotons, striking a hydrogen target, creates electron-positron pairs; occasionally the positron might link up with one of the antiprotons. One direct approach involves colliding antiproton and positron beams together but, according to Gabrielse, this would most likely result in the particles bouncing off each other rather than mating. Scientists expect that antihydrogen, once it can be made, will be useful in the study of gravity and quantum mechanics.

Studying electrical charges

The charge of the antiproton is usually assumed to be exactly the same size (although opposite in charge) as that of the proton, but is this true? The electrical charge of antiprotons, and also positrons, has been studied using data from cyclotron-frequency experiments (which monitor the behaviour of particles in a magnetic field) comparing protons with antiprotons and electrons with positrons, as well as spectroscopic measurements of short-lived states containing antimatter, such as positronium and anti-protonic atoms. Richard Hughes[9] and B.I. Deutch[10] have calculated that the charges of the positron and electron are equal to about one part in 10^8, while the charge of the antiproton equals that of the electron to about one part in 10^5. The precision of these calculations would improve if researchers could study antihydrogen.

Even if atoms are completely neutral, is it true that the centre of positive charge in the atom coincides with the centre of negative charge, or do atoms have electric dipole moments? Searches for non-zero electric dipole moments in atoms have the potential to test supersymmetry, a theory that emphasizes a hypothetical symmetry between fermions and bosons in an effort to unify the electroweak and strong forces into a single framework. This model predicts the existence of a non-zero electric dipole moment at the level of 10^{-27} cm (times the charge of the electron) or, equivalently, that in some atoms the centres of negative charge and positive charge should be offset by a very tiny amount, less than 10^{-27} cm (per unit charge). When the tabletop dipole experiments being carried out[11] reach the levels of precision needed for making this sort of measurement – they are currently a factor of 10 away in precision – they will complement accelerator experiments seeking to study supersymmetry.

CONDENSED MATTER PHYSICS

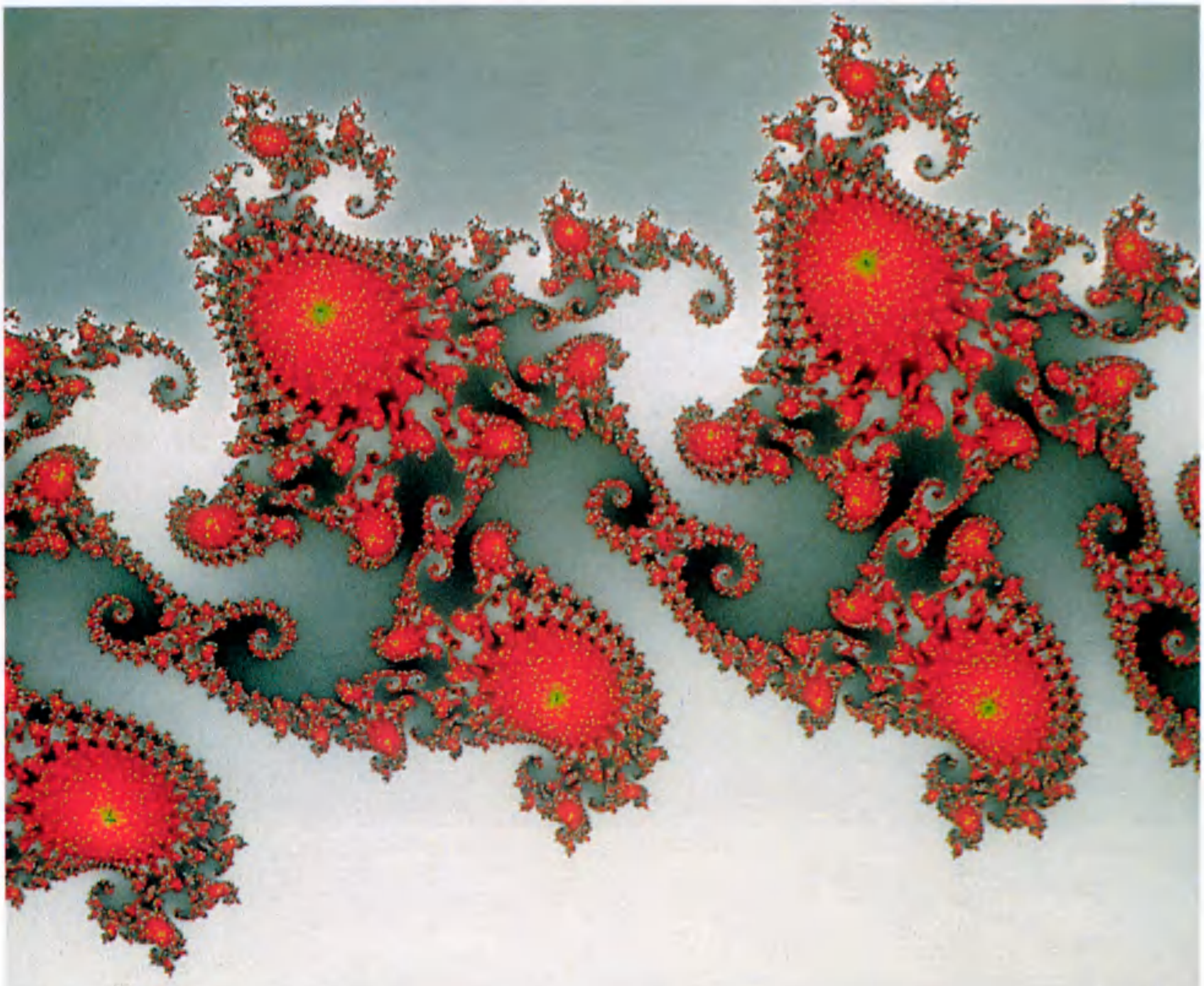
Condensed matter physics is the study of the properties of matter in the solid, liquid and dense gaseous phases. Matter in this instance is made not of isolated quarks or protons or atoms but rather of millions of atoms or molecules (10^{24} in a cubic centimetre). A host of properties – optical, electrical, mechanical or thermal – that do not apply to atoms in isolation are of fundamental importance to the study of solids. The exploration of these properties leads to new physics insights and also promotes new technological products and techniques.

Indeed, many of today's prominent technologies, such as computers, lasers and telecommunications, depend on the development of new materials with novel properties. Superconductors are one example. Superconductivity, in which certain materials lose all electrical resistance when cooled below a special transition temperature, may lead to faster, more energy-efficient devices. The benefits of superconductivity are partially offset by the cost of cooling the materials, and so it is desirable to discover compounds which remain superconducting to as high a temperature as possible. Currently the material with the highest transition temperature (133 K) is a mercury-containing copper oxide compound developed by scientists at the ETH laboratory in Zurich, Switzerland.

Another crucial factor in improving the performance of electrical devices (speed, energy consumption, storage capacity, etc.) has been the increased level of

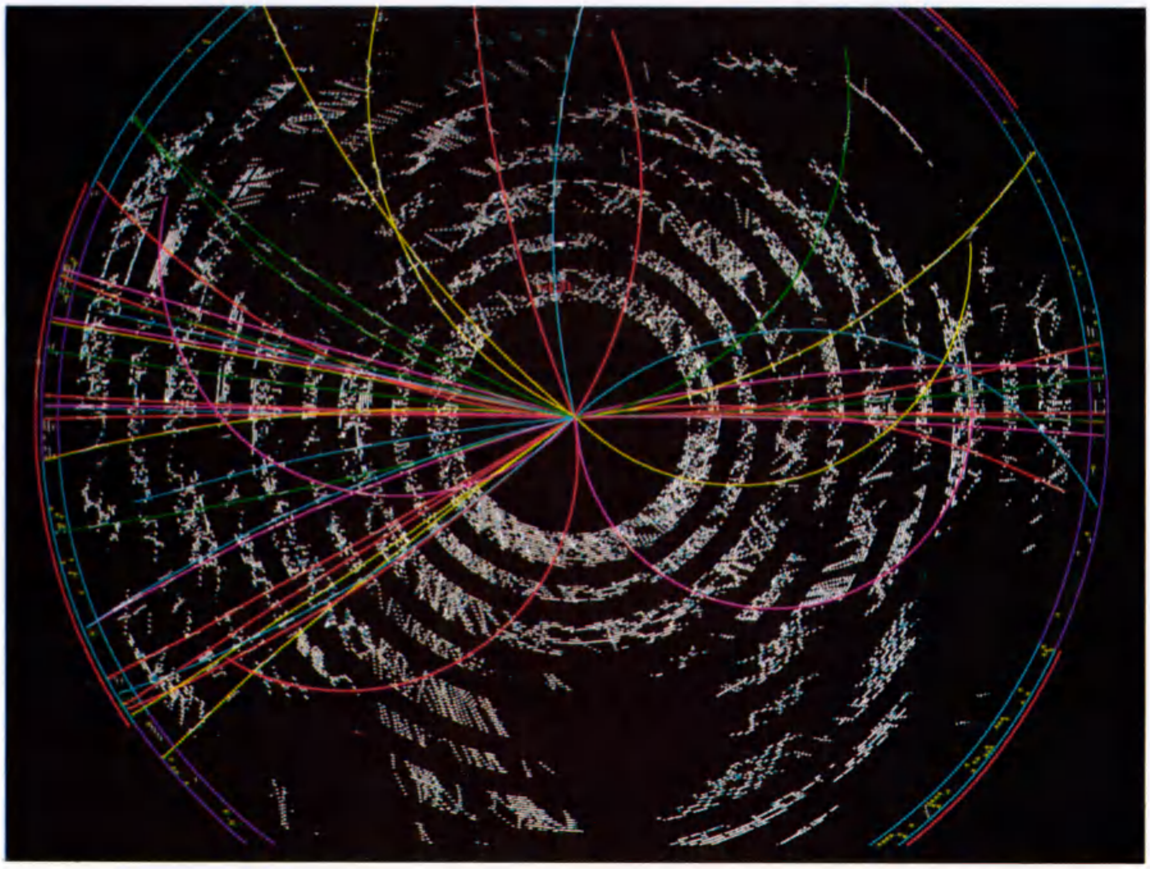
[7]Stanford University, California, USA. [8]Harvard University, USA. [9]Los Alamos National Laboratory, New Mexico, USA. [10]University of Aarhus, Denmark. [11]at the University of Massachussetts, Amherst, USA, University of Washington, Seattle, USA, University of California at Berkeley, USA, and Yale University, USA

FIGURE A
FINE STRUCTURE OF THE BOUNDARY OF THE MANDELBROT SET



Source: Peitgen, H.-O. and Richter, P.H. (1986) *The Beauty of Fractals*, New York, Springer-Verlag 85, Map 44.

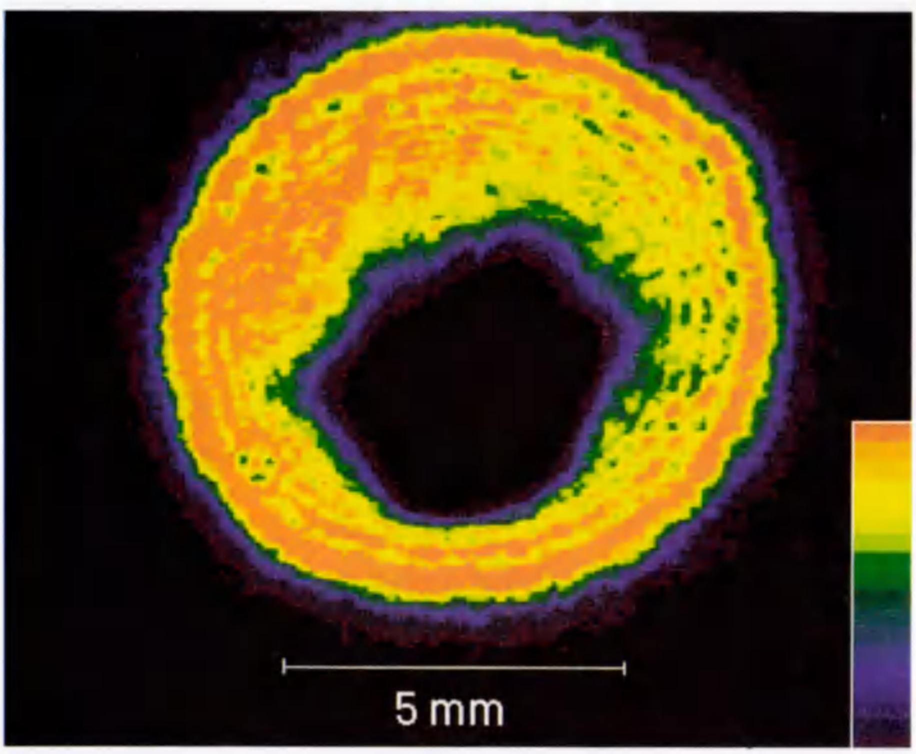
FIGURE B
A PROTON-ANTIPROTON COLLISION



Each coloured track in this computer-reconstructed image represents a different elementary particle emitted from a proton-antiproton collision at the Fermi Accelerator Laboratory (Fermilab). Physicists at Fermilab are currently engaged in the search for the elusive top quark which will provide an improved understanding of the structure of matter.

Photo courtesy of Fermilab.

FIGURE C
ATOM DENSITY



The shadow of atoms contained in a magneto-optic trap at MIT. The density of atoms – almost 10^{12} per cubic centimetre – is so great that no laser light can pass through.

FIGURE D
THE DETECTOR AT THE HADRON-ELECTRON RING ACCELERATOR (HERA): A VERTICAL CUT ALONG THE BEAM

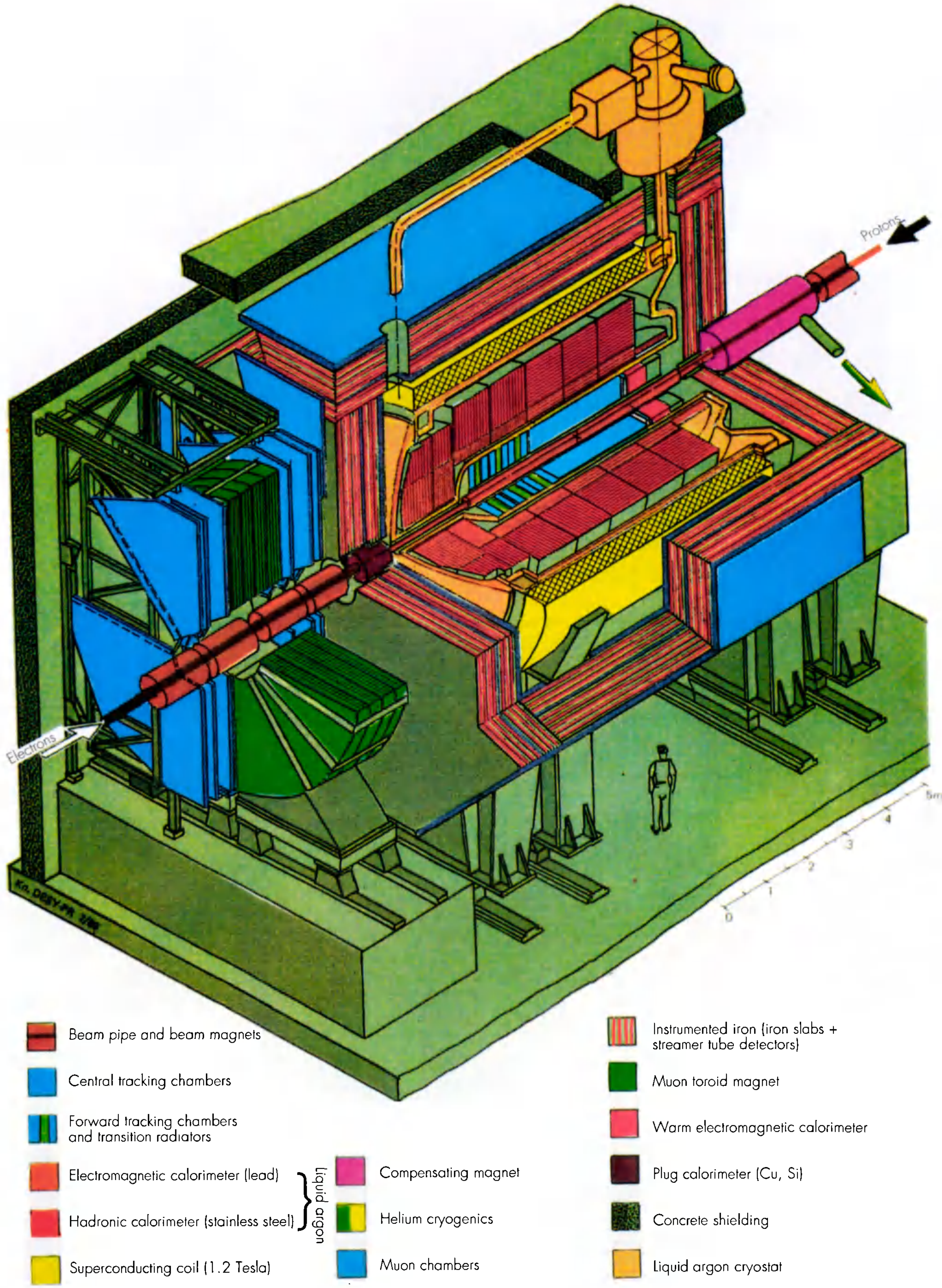
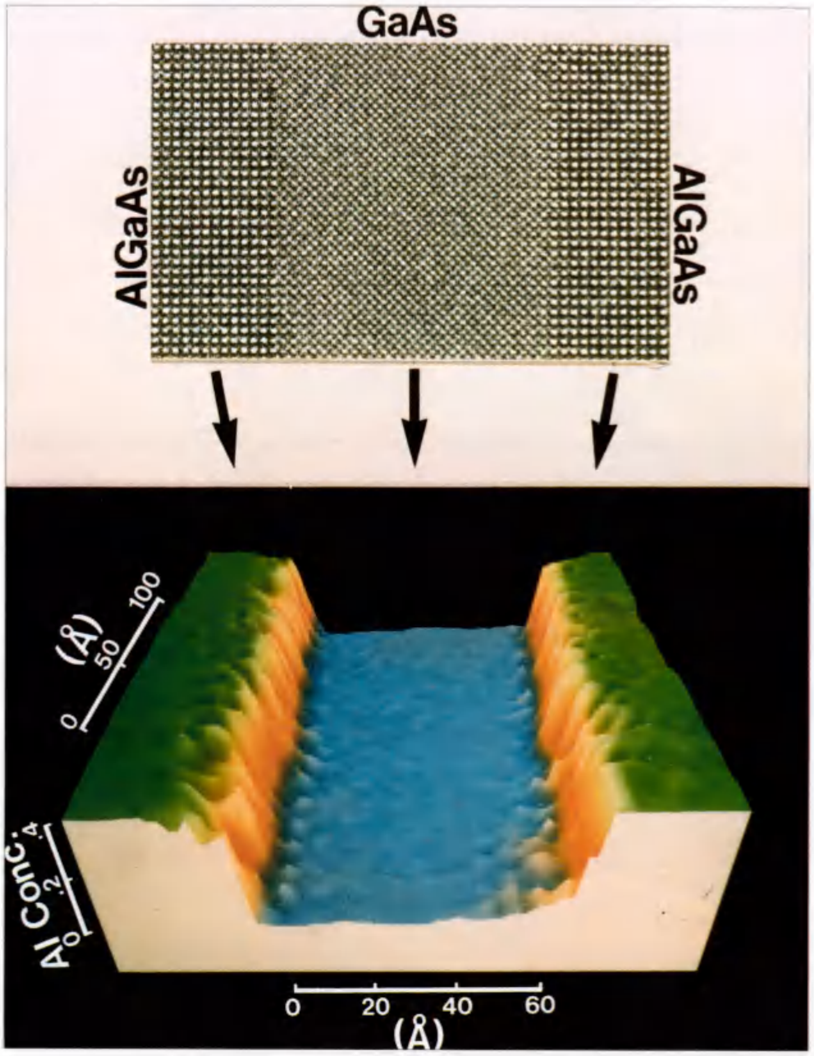


FIGURE E
A 'QUANTUM-WELL'



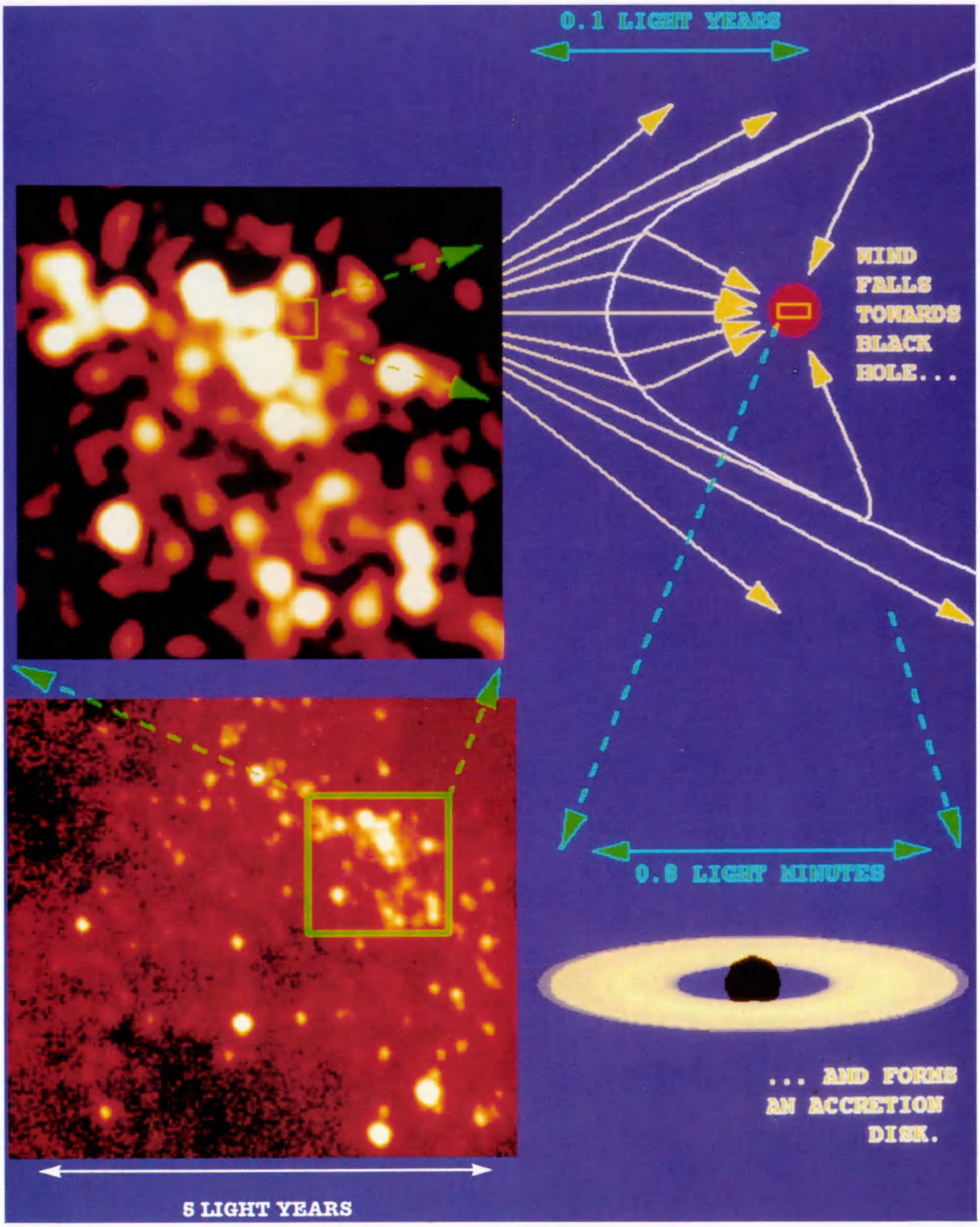
Top: atomic-resolution micrograph of a quantum-well structure consisting of two layers of AlGaAs with a layer of GaAs sandwiched between.
Bottom: a 3-D plot showing how the aluminium concentration drops off within one or two atomic layers.

Photo courtesy Ourmazd, Kim and Taylor (AT&T Bell Labs).

FIGURE F
X-RAY IMAGE OF THE MOON AS RECORDED BY THE GERMAN ROSAT IN JUNE 1990

Source: Rosat.

FIGURE G
INFRARED IMAGE OF THE INNER FIVE LIGHT YEARS OF OUR GALAXY

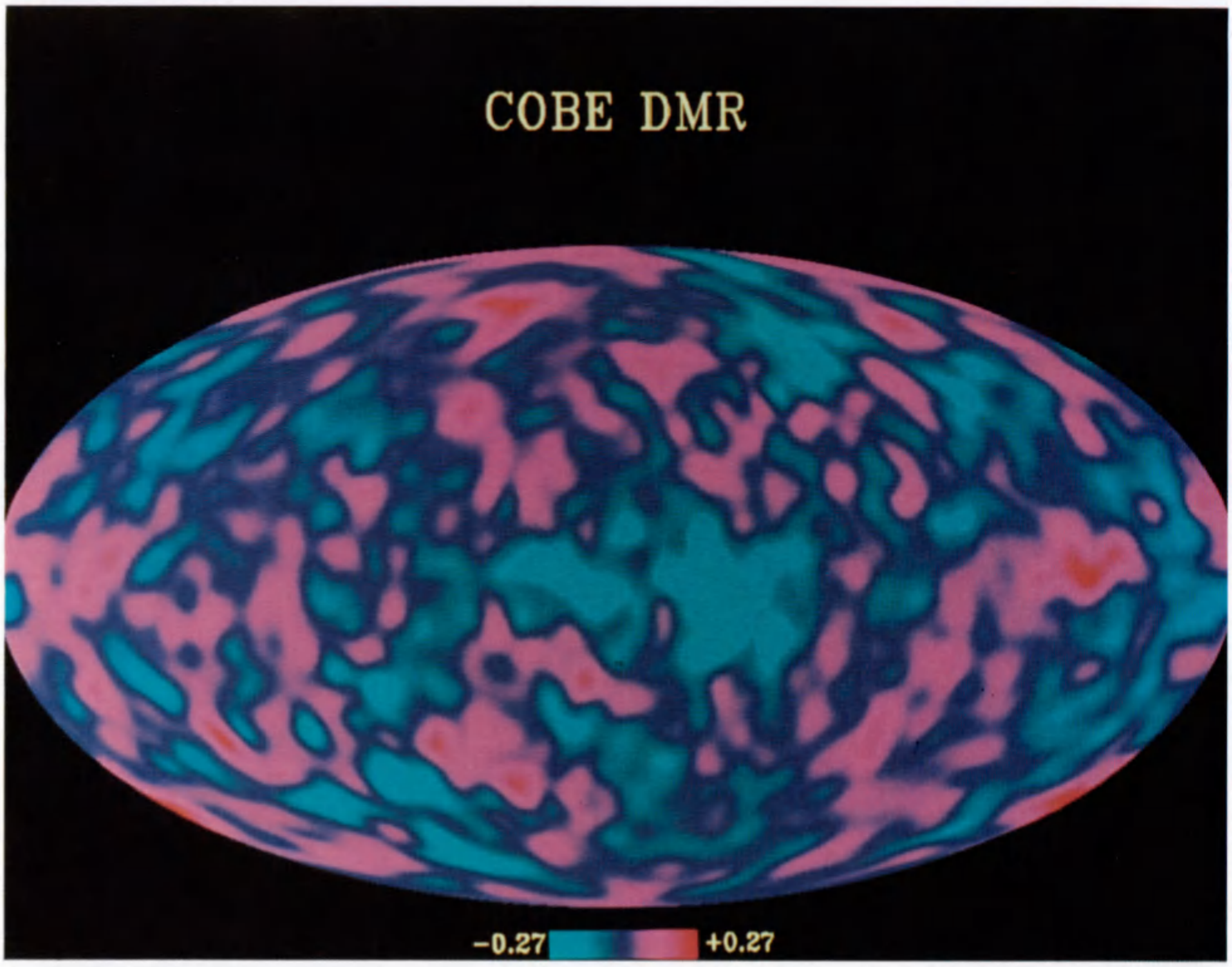


Infrared image of the inner five light years of our galaxy made using the Steward Observatory telescope at Kitt Peak, near Tucson, Arizona. At the centre of this super-dense star cluster is the massive black hole candidate Sgr A*. In the upper left hand corner a processed image 'zooms in' on the inner 1.5 light years of the lower image. Here, one can clearly see (for the first time) a faint (but real) point source of infrared emission at the location of Sgr A* (the location of Sgr A* – known from radio maps – is inside the small green box in this upper left hand image).

The luminosity of this point source is in agreement with that predicted by a model of Sgr A* as a million solar mass black hole. In this model the strong local stellar 'winds' are captured by Sgr A*'s gravitational attraction (see diagram in the upper right hand corner of figure). Just before reaching the black hole, the wind's angular momentum forces the infalling wind to settle into a thin disk (see lower right). This disk glows in the infrared (due to friction), and is most likely inclined to our line of sight (see photo). The friction between the gas particles causes the gas to slowly pass through the disk, and after many orbits finally fall into the black hole.

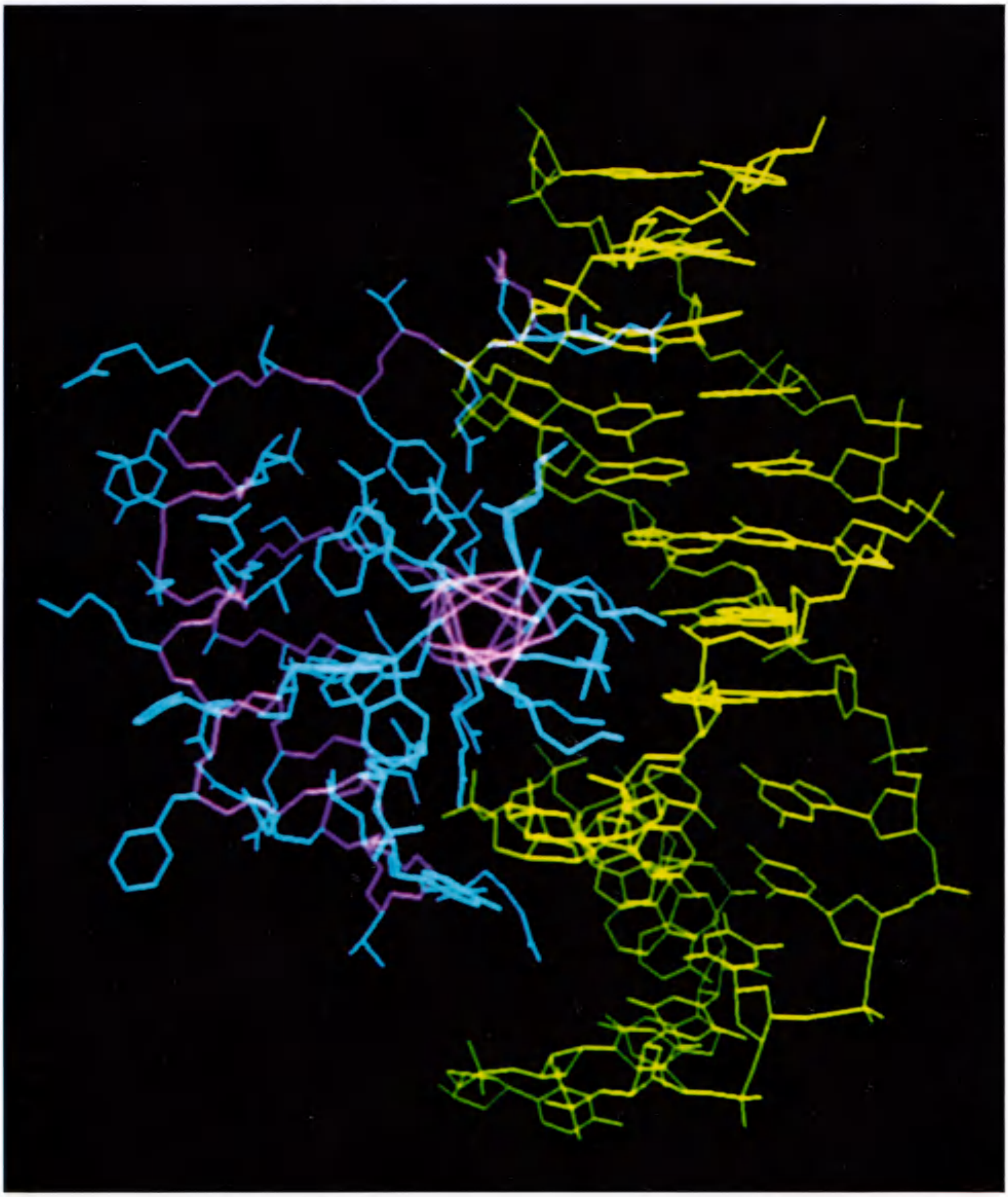
Photo courtesy Laird M. Close, Steward Observatory, University of Arizona

FIGURE H
IMAGE FROM THE COSMIC BACKGROUND EXPLORER (COBE) SATELLITE



The Differential Microwave Radiometer (DMR) on board COBE reveals small fluctuations in the temperature of the universe across the sky: the red and blue patches correspond to areas which are slightly warmer or cooler than the average temperature respectively.

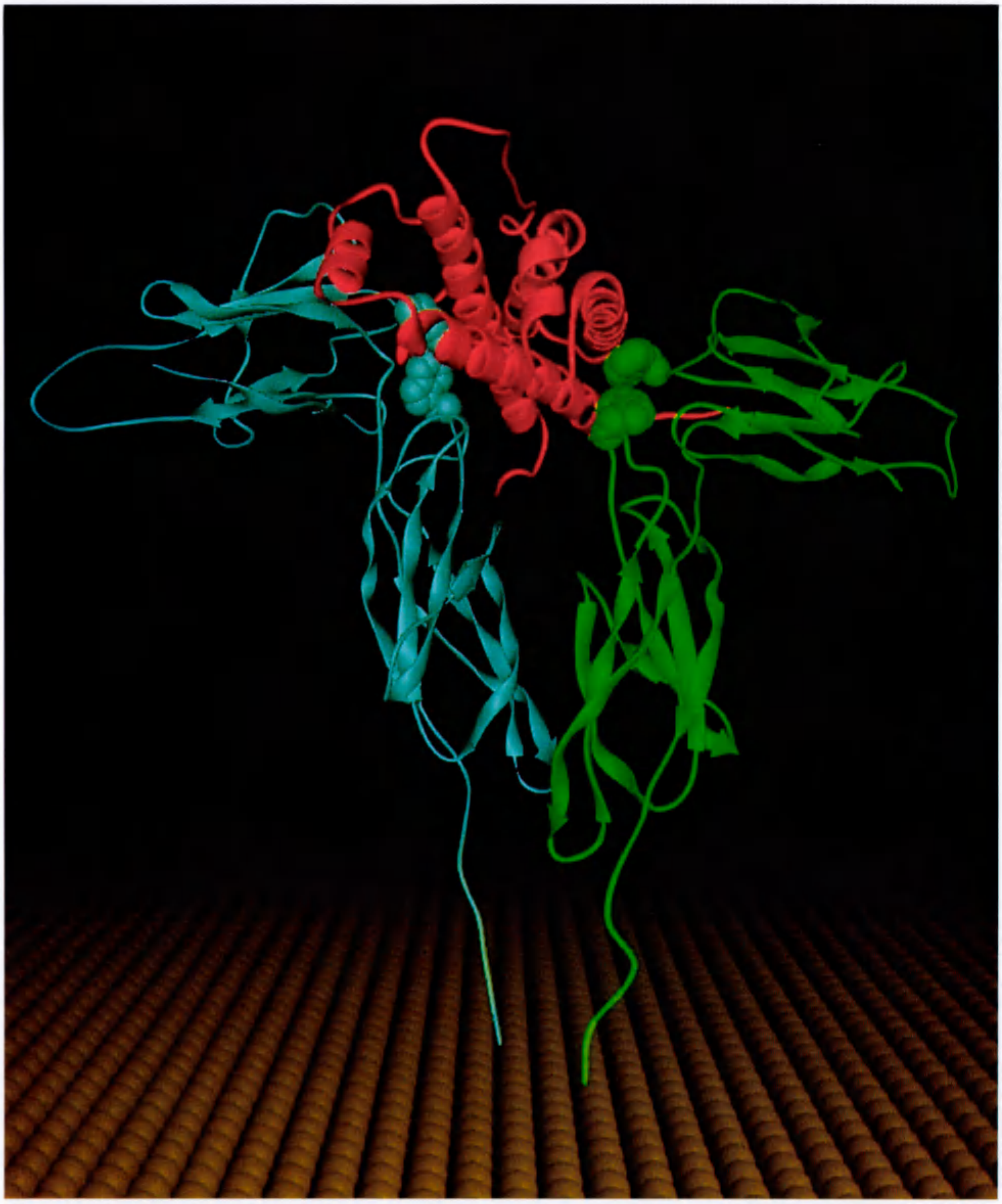
FIGURE I
THREE-DIMENSIONAL STRUCTURE OF A DNA SWITCH



A protein hand (blue and magenta) interacting with a switch on the double helix of DNA (yellow) as visualized in three dimensions by means of nuclear magnetic resonance technology.

Source. Gehring, W.J. and Wuthrich, K. Structural and functional analysis of homeodomain-DNA interactions, *Structure*, 25 April 1993: v.

FIGURE J
LIGAND-RECEPTOR BINDING



A single molecule of human growth hormone (red) bound to two molecules of its receptor (blue and green) as visualized in three dimensions by means of X-ray diffraction technology. One end of each receptor molecule is shown attached to a cell membrane.

Source: Kossiakoff, A.A., Ultsch, M. and de Vos, A.M. Human growth hormone-receptor complex, *Structure*, 25 April 1993: xvii.

miniaturization. This tendency may soon lead to discrete components nearly as small as, or at least mimicking the behaviour of, individual atoms. Such 'artificial atoms' are manmade, essentially zero-dimensional systems – usually involving specially tailored nanometre (nm) semiconductor structures – in which the presence or movement of single electrons can be important. One prominent example is the quantum dot, a pointlike 'quantum-well' structure (in which electrons in a very thin semiconductor layer are trapped between two outer semiconductor layers) that can be fashioned as a tiny stump on a substrate by selectively etching away surrounding material, or as a pointlike isolated region inside a semiconductor sandwich by pinching off a small volume of the material with electric fields using overlying metal electrodes. (See Figure E, colour section p. iv.) In such a system, as in atoms, quantum mechanics dictates that particles confined in a small enough space (roughly 10 nm for electrons in semiconductors) can assume only discrete energies.

Single-electron devices

If quantum dots are artificial atoms, then a planar array of a million such dots could constitute a sort of artificial crystal. Scientists have created such arrays but have not yet been able to control crystalline uniformity and the placement of electrodes sufficiently for studying the energy band structure in this system as one does for a 'real' crystal. In addition to spatial-confinement effects, charge-quantization effects can also influence the behaviour of dots. That is, dots can be made to accept only a single electron or just a few, and their coming and going can be monitored; as the voltage is turned up, new electrons are able to overcome the efforts of the electrons already on the dot to exclude newcomers through an electrostatic 'Coulomb blockade'. This dependence on individual electrons may make possible a range of new devices.

In fact, single-electron devices may one day make it possible for integrated circuits to have as many as 10 billion electronic devices in a square centimetre, a density 1 000 times greater than that believed feasible for conventional integrated circuits. In development since the mid-1980s, these devices consist of two electrodes (typically 30 nm wide) separated by a 1 nm-deep insulating layer through which single electrons can tunnel. In the last several years, researchers have built two-junction devices that share a middle electrode. These devices are called single electron transistors, because, like conventional transistors, their current can be controlled by modifying the surface charge on the middle electrode, making it an ideal element for an integrated circuit. A circuit made of single-electron devices, however, would have to be operated at a temperature of 4 K or below to reduce thermal effects which disturb the movements of single electrons in the solid.

Optical properties of semiconductors

Optical properties of semiconductors are also important since future computer and communications systems will probably be a hybrid of electronics – information encoded in the form of electrons – and photonics – information encoded in the form of photons. In this regard, silicon, notwithstanding its service in countless electronic circuits, is troublesome since it does not ordinarily emit light. In semiconductors using elements from columns III and V of the Periodic Table, such as GaAs, the energy released in the recombination of electrons and holes (holes are merely the absence of electrons) can take the form of a photon; this process can be harnessed in opto-electronic devices. But in silicon, by contrast, the recombination energy usually appears as heat. Leigh Canham and other scientists[12] have succeeded in getting light (of all colours) out of tiny silicon filaments made by immersing silicon in a bath of acid, which etched out a honeycomb of slender silicon structures. Scientists have hypothesized that the light may derive from some quantum effect; that is, the very tiny size of the silicon filaments (only a few nanometres in some cases) altered the 'band structure', the sequence of allowed energy levels, in the material.

Light-emitting properties

Meanwhile, the light-emitting properties of other semiconductors are also being utilized for the purpose of device applications. Compounds using elements from columns III and V in the Periodic Table (such as GaAs) readily produce light, but chiefly in the infrared. To get shorter wavelengths in the visible range, scientists have been studying compounds (such as ZnSe) which combine

[12]Royal Signals and Radar Establishment, UK

elements from columns II and VI; band-gap energies in these compounds usually exceed 2 eV. Problems with doping and with establishing a suitable crystalline match-up between the light-emitting material (II-VI) and substrate material (III-V) have hindered the development of devices. New epitaxial techniques (in epitaxy very thin layers of different atoms can be laid down one on top of another) have partially changed this. For example, lasers using type II or type VI elements have operated at power levels up to 700 megawatts, at temperatures up to room temperature, and at duty cycles (the fraction of time the laser is on) as high as 40%. Light-emitting diodes made from type II-VI semiconductors have radiated at wavelengths as short as 490 nm. Before such blue/green lasers can be used commercially, several technical problems must be overcome, in this case a low energy-into-light conversion efficiency and overheating.

The 'forbidden gap'

A 'semiconductor' for light waves, a material in which certain photon wavelengths would be excluded – creating, in effect, a photon band gap analogous to the forbidden electron energy bands in semiconductors – has been developed by Eli Yablonovitch and his colleagues[13]. They drilled three sets of holes into the top surface of a slab of dielectric material, creating a crisscross structure. Theorists had predicted that such a honeycomb geometry would result in the exclusion of light at certain wavelengths. Indeed, when Yablonovitch sent microwaves into one sample (which, because of the holes drilled inside, was 78% empty) he discovered the looked-for 'forbidden gap', a range of frequencies for which light simply will not pass through the material. By proper tailoring of the holes, optical wavelength bands can also be induced; this will make these 'photonic crystals' useful in a variety of research areas, such as atomic physics and microelectronics.

One recent application of this concept was an antenna mounted on a photonic crystal developed by scientists at the Massachussetts Institute of Technology (MIT) Lincoln Laboratory and Yablonovitch, who built a photonic crystal-antenna setup which can couple microwave radiation to devices on integrated circuits. This configuration allows integrated-circuit devices to receive microwave radiation or, conversely, to convert electric current into microwave signals. The configuration traditionally used for this purpose, antennae on semiconductor substrates, transmits only a few per cent of their total power into the air; the rest is radiated into the semiconductor. The antenna has much higher efficiency because the photonic crystal on which it is mounted has a sizeable energy gap in the microwave region.

SOLAR SYSTEM

Powerful telescopes and satellite visits to all the planets (except Pluto) have taught scientists much about the solar system in recent years. Even computers help in the exploration. For example, computer studies simulating the evolution of the solar system over millions of years show evidence for chaotic behaviour. That is, even equipped with the laws of motion, long-term trajectory forecasts become less reliable because of the complicated interactions among the planets. Gerald Sussman and Jack Wisdom[14] have carried out the most detailed calculation yet of the motions of the planets into the far future – over a 100 million year period – and found that after only about 4 million years planetary positions cannot be predicted with any certainty. These new calculations, which required considerable computer time, confirm earlier (1989) but less detailed studies by Jacques Laskar[15] indicating chaotic behaviour throughout the solar system.

The 'solar neutrino problem'

The Sun sits at the centre of the solar system, and in the centre of the Sun ghostly particles called neutrinos are created in the fusion reactions that take place there. These neutrinos travel out through the Sun and on to the Earth, where they can be detected indirectly. The standard solar model, a model that encapsulates the latest theory of nuclear reactions inside the Sun, predicts that the Homestake neutrino detector, operated for 20 years by Ray Davis in a South Dakota gold mine, should observe an average of 1.8 solar neutrinos per day. Instead Davis' observed rate has consistently been much lower than this. This 'solar neutrino problem' has in recent years been tackled by two other groups, and they too record puzzling results. Over a three-

[13]University of California at Los Angeles, USA. [14]Massachussetts Institute of Technology, USA. [15]Bureau des Longitudes, Paris, France

year period, the Kamiokande II detector in Japan sees a neutrino rate about half that expected by the standard model, roughly equal to Davis' average rate for the same period. Unlike Kamiokande and Homestake, which are sensitive only to the relatively high-energy neutrinos released in the beta decay of boron in the Sun, the Soviet-American Gallium Experiment (SAGE) in the Caucasus mountains is designed to observe the lower-energy neutrinos coming from the more plentiful proton-proton fusion reactions in the Sun. In five months of running, SAGE observed essentially no neutrinos at all, further deepening the mystery. Some theorists believe that one possible explanation is that solar neutrinos may be 'oscillating' from one neutrino type (electron, muon, tau) to another on their way to the Earth and thus evading detection.

A fourth detector, Gallex, has observed neutrinos at a rate of 83 Solar Neutrino Units (1 SNU = 10^{-36} neutrino captures per atom per second). This multinational collaboration detects solar neutrinos in a 50 000-litre bath of gallium chloride installed in the Gran Sasso tunnel under the Abruzzi mountains in Italy. The neutrinos, arising largely from proton-proton fusion reactions in the Sun, but also from the decay of beryllium and boron in the Sun, travel to Earth, and enter the detector, where they convert a gallium-71 nucleus into a germanium-71 nucleus. The radioactive germanium is extracted every three weeks and monitored closely in a separate vessel. The calculated production rate of 83 SNU is to be compared with theoretical estimates that range from 124 to 132 SNU. For the 132-SNU estimate, 74 SNU should come from (relatively low energy) proton-proton reactions, 34 SNU from beryllium-7 decays, 14 SNU from boron-8 decays, and 10 SNU from nitrogen-13 and oxygen-15. The Gallex results are much closer to the theoretical estimates than those from the South Dakota or Kamiokande detectors, which are sensitive only to higher energy neutrinos. The Gallex results are in stark contrast with those from SAGE.

Venus still volcanically active

Moving from the Sun to Venus, recent pictures taken by the Magellan spacecraft, which has created the first global map of Venus, show that the second planet is still volcanically active. For example, an Australian-sized lava flood north of Venus' equator contains no meteorite craters, implying that the lava is no more than tens of millions of years old. Most of Venus' impact craters seem to be relatively young; older craters were possibly covered by a number of great lava flows. Other studies show that Venus does not have 'mid-ocean' ridges like those on Earth. The notion that ridges in the Ovda Regio section of Venus were caused by crustal spreading was dispelled by new radar pictures from the Magellan spacecraft.

Lightning on Venus may have been observed in a fly-by by the Galileo spacecraft. Because of the qualities connected with Venus' thick atmosphere, most planetary scientists never considered Venus a prime candidate for lightning. However, Galileo's detection of six lightning-like bursts of electrical energy have jolted investigators to search for explanations. One possibility is that lightning on Venus may arise from volcanoes, specifically from particles rubbing against each other in the flows of hot rock rising to the surface. Such volcanic plumes have been known to cause lightning on Earth. Indeed the Magellan spacecraft has detected (and continues to look for) signs of volcanic ash on Venus, although active volcanoes are believed to be rare on the planet.

Jupiter and beyond

Ulysses, the first spacecraft to visit Jupiter (February 1992) since the Voyager missions in the 1970s, is destined to pass beneath the Sun's south pole in the summer of 1994. In the meantime its side trip to Jupiter has supplied plentiful information about the Jovian environment: the magnetosphere was found to be inflated to a size much larger than at the time of the Voyagers; the presence in the magnetosphere of sulphur and oxygen ions, produced mostly at Jupiter's volcanic moon Io (at a rate of about 1 tonne per second) was confirmed; very little dust was found near Jupiter; Io's principal volcano, Loki, was quiet. Ulysses sampled the Jovian magnetic field, the strongest in the solar system. The magnetosphere was flatter than expected. Mission scientist André Balogh partly attributes this to the presence of a huge billion-ampere current flowing in the Io Torus, a sheet of sulphur and oxygen ions issuing from Io.

Far beyond the orbit of Pluto, and marking the very edge of the solar system, is the heliopause, where the solar wind particles streaming out from the Sun meet the directional flow of interstellar-medium particles. Recently, radio signals from the heliopause were detected by the two Voyager spacecraft. Mission scientists provided this explanation: a powerful solar flare event in May/June 1991 caused a surge of solar-wind particles which subsequently interacted with the heliopause, setting up huge radio bursts (at more than 10^{13} watts, the most powerful radio source in the solar system) detected by the Voyagers beginning in July 1992. High in power but low in frequency (2-3 kilohertz), the radio signals could not be detected in the inner solar system. However, Voyager 1, at a distance of 52 AU (an astronomical unit – AU – is the distance between the Earth and Sun), and Voyager 2, at 40 AU, were well placed to make a measurement. From the timing of the signals the distance to the heliopause could be estimated to be between 80 and 130 AU.

STARS AND GALAXIES

Seeing beyond our solar system out to other stars and galaxies requires powerful telescopes. In the visible-wavelength range, the orbiting Hubble Space Telescope has made notable observations despite its somewhat flawed focusing arrangement, a problem which may soon be cured by the installation of corrective optical components. Meanwhile, several prominent ground-based optical telescopes are nearing completion. The Keck telescope, at the summit of Mauna Kea in Hawaii, has 36 hexagonal mirror segments and a diameter of 10 m and is the world's largest optical and infrared telescope, with four times the light-gathering power of the 200-inch Hale telescope. The Very Large Telescope (VLT), being built at Cerro Paranel, a mountain top in Chile, by the European Southern Observatory (ESO) will be even bigger. The VLT will consist of four 8.2-m telescopes, the first of which should be installed by 1995; the equivalent 16-m diameter of the composite device will be much larger than the 10-m Keck or 6-m Hale telescopes.

An additional factor in improving astronomical observations is the increasing use of digital technology. According to Larry Smarr[16], astronomy will be the first all-digital science. Charge-coupled devices (CCDs), which convert incoming photons into tiny electrical signals, are largely taking over as a means of making observations; CCDs are efficient (up to 80% of incoming photons are recorded as compared to 2% for photographic film) and the data is in a form that can be readily processed by computer. This will facilitate large-scale, semi-automated projects, such as the University of Chicago's five-year plan to chart the position of a million galaxies and 100 000 quasars.

Seeing beyond the visible

Astrophysics has also made great strides in charting the sky at wavelengths outside the visible. X-ray satellites such as the German craft Rosat and the Japanese craft Ginga, gamma ray satellites such as the US Gamma Ray Observatory and the Japanese solar-observing satellite Yokhoh, and ultraviolet satellites such as ASTRO and the Extreme Ultraviolet Explorer have uncovered many new celestial objects and have obliged astronomers to account for many new phenomena. Rosat, for example, has taken pictures of the sky further out in distance, or equivalently further back in time, than any other X-ray images previously recorded. (See Figure F, colour section p. iv.) These pictures reveal a great density – with a suggestion of clustering – of quasars at redshifts between one and two. Rosat has spent much of its observing time doing an all-sky survey at X-ray wavelengths.

Rosat has also scanned the cosmic X-ray background which, first detected in 1971, may consist largely of radiation from discrete quasars. Rosat scientists looked at a very select far-distant field of the sky and found 39 X-ray sources; follow-up studies with an optical telescope showed that 24 of these were quasars. The scientists conclude that at least 30% (but perhaps almost all) of the X-ray background (at least in the 1-keV energy range) arises from quasars.

Violence in the gamma-ray range

At even more energetic wavelengths, in the gamma-ray range, the universe looks particularly violent. In one single-week interval, for example, quasar 3C279 emitted about 10^{54} ergs of energy in gamma rays, roughly the same energy you would get if all the particles in our Sun were to be annihilated into radiation. Although scientists don't yet know the nature of the engine which produces such

[16]University of Illinois, USA

stupendous supplies of gammas, the sources of gamma radiation can at least be inventoried and studied by the Compton Gamma Ray Observatory (GRO), launched in April 1991. GRO has now discovered, in addition to 3C279, three new quasars that emit gamma rays (although not on a continuous basis) at a rate of 10^{48} ergs per second. The first two discovered – Crab and Vela – beam gammas twice every pulsar rotation; the third – Circinius – does so only once.

Other GRO results include the observation of more than 600 gamma bursters, mysterious sources of short-lived, energetic gamma bursts; their distribution across the sky remains isotropic, almost surely ruling out the notion that they originate in the plane of our galaxy. Two leading explanations for the isotropy entail interesting problems of their own: if the bursters sit in the galactic halo, then the halo would have to be much larger than thought before, more than 150 000 light years in radius. If the bursters are extragalactic, how could it be that so many gammas had travelled so far?

Finally, GRO has monitored the electron-positron annihilation radiation from the centre of our galaxy and found that, unlike previous, less sensitive measurements by other detectors, the radiation does not seem to vary with time.

Ultraviolet and infrared ranges

The extreme ultraviolet (EUV) is a wavelength range (5-100 nm) impossible to see through the atmosphere with telescopes on the ground. The EUV detector on the Rosat satellite has therefore opened up a whole window on astronomy. British scientists in charge of Rosat's EUV survey have reported more than 700 sources, whereas only a dozen were previously known. One consequence is a downward revision of the estimated density of hydrogen in the region of the solar system; it was thought that such hydrogen would limit EUV radiation, much of it coming from hot stars, from reaching the Earth.

Because EUV is absorbed by interstellar gas, which is mostly hydrogen and helium, it came as something of a surprise that the Rosat and the Extreme Ultraviolet Explorer (EUVE) satellite telescopes could see as far as they do. In this case EUV measurements are benefiting from the fact that our solar system seems to sit in a bubble at least partially cleared of interstellar matter, perhaps by past supernovas. This allows the telescopes to see objects (mostly hot white dwarfs) hundreds of light years away. In certain directions viewing conditions are so good that faraway galaxies can be seen.

At radio wavelengths, astronomers have found signs of planets in orbit around pulsars. Alexander Wolszczan[17] and Dale Frail[18] have reported evidence for two and possibly three planets around the pulsar PSR 1257+12. The two more substantially inferred planets have orbits about the size of Mercury's around our Sun, whereas the third planet, if it exists, has an orbit about the size of Earth's. Support for the planet hypothesis comes in the form of the measured delay in the expected arrival of radio waves from PSR 1257+12.

At infrared (IR) wavelengths, new studies address the subject of whether there is a black hole at the centre of our galaxy. In particular a source of IR radiation has been discovered at the location of the object called Sgr A*. The new IR results reinforce the idea, established by previous measurements of Sgr A* at radio, X-ray and gamma wavelengths, that a black hole resides at the core of the Milky Way. Laird Close[19] has presented pictures of the galactic core at wavelengths of 1.6 and 2.2 microns (μm) made using the 2.3-m telescope at Kitt Peak. (See Figure G, colour section p. v.) The observations, employing adaptive-optics techniques in the infrared for the first time, had sufficient resolution to show that the IR source was no larger than 0.006 light years across. Arizona astronomer Joseph Haller has presented separate IR studies of the velocities of stars as a function of distance out from Sgr A* showing that the velocities increased from nearly zero at a distance of 1.4 light years from Sgr A* to a velocity of nearly 100 km per second at a distance of 0.7 light years. This pattern, plus the determination that there must be at least 100 times more mass inside the 0.7 light-year distance than can be accounted for by the observable stars alone, suggests to Haller that there should be a 900 000-solar-mass black hole at Sgr A*.

Do black holes exist?

Many astronomers believe that supermassive black holes exist, but won't be convinced merely by the impressive increase in luminosity of starlight toward the centre of certain galaxies. According to Alan Dressler[20], conclusive

[17]Cornell University, New York, USA. [18]National Radio Astronomy Observatory, New Mexico, USA. [19]University of Arizona, USA. [20]Carnegie Institution, USA

evidence for black holes would come from the spectroscopic study of the movement of stars in the vicinity of the hole. The necessary high resolution may come with a rejuvenated Hubble Space Telescope or with the new optical telescopes being built atop Mauna Kea and in Chile. Based on preliminary studies of star motion, the galaxies most likely to be harbouring supermassive black holes are Andromeda, its satellite galaxy M32, and NGC3115 (whose candidate black hole would have a mass of more than a billion solar masses). In the long run, it may be easier to hunt for black holes in relatively placid galaxies like these, where the lack of the energy glare associated with active galaxies can only make easier the task of viewing star motion near the galactic core. As for our own presumed resident black hole, studies of the Milky Way's central precinct are hindered by a viewing problem of another sort, namely the presence of dust. Nevertheless, indirect measurements of star motion are consistent with the idea of a black hole at the galactic core.

COSMOLOGY

Cosmology is the study of the origin, evolution and overall structure of the universe. Like particle physics, cosmology has a 'standard model', a consensus theory which holds that the universe was created in a Big Bang, an explosion of space itself, after which the universe expanded and cooled. Tiny inequalities in the distribution of matter throughout the universe later led to the formation of stars, galaxies and large clusters of galaxies.

Observationally, the largest structure in the universe that can be studied is the cosmic microwave background (CMB), the bath of radiant energy left over from the Big Bang. It had long been thought that the microwave background should exhibit tiny fluctuations corresponding to the sort of matter irregularities that resulted in the formation of galaxies. For many years, however, measurements seemed to indicate that the CMB was smooth. If this were really true, then where were the 'seeds' from which galaxies grew?

Finally, the Cosmic Background Explorer (COBE) satellite discovered the primordial seeds, at a level of one part per 100 000. Prevailing theories of cosmology, such as the inflationary Big Bang model (according to which the early universe underwent a special extraordinary period of inflation before settling down into the current rate of expansion), predict that measurements of the cosmic microwave background (CMB) should reveal small fluctuations in the temperature of the universe across the sky. These fluctuations – patches of sky with temperatures slightly higher or lower than surrounding areas – correspond to regions of the early universe with slightly greater or lesser concentrations of matter. This pattern of matter would serve as a sort of template for cosmic evolution. Small as they are, the observed patches of enhanced density are thought to have provided enough of a gravitational 'valley' into which surrounding matter could collect. This process would presumably lead after billions of years to the clustering of galaxies we see today.

The fluctuations observed by the COBE scientists (see Figure H, colour section p. vi) amounted to faint temperature variations of roughly 30 microkelvins on top of an average sky temperature of 2.73 K. George Smoot[21], head of the team which operated the Differential Microwave Radiometer (DMR), one of three principal instruments on board COBE, reported that these results were based on the meticulous computer analysis of a year's worth of data. This analysis had to carefully subtract competing microwave emissions from such nearby objects as the Earth and the Milky Way galaxy, and to take into account the effect of the Earth's movement (and that of our galaxy) through the universe, a motion that imposes a dipole shift on the pattern of temperature measurements across the sky.

Edward Wright[22] asserted that the new results supported some cosmologies, such as those that prescribe the existence of dark matter, and ruled out others, such as those suggesting the existence of 'textures', wrinkles in space-time. Without dark matter, for example, the temperature (or equivalently matter density) fluctuations should have been larger than those seen.

During the inflationary expansion of the early universe gravitational waves may also have been an important ingredient in the organization of matter and may account for part (perhaps even a large part) of the measured anisotropy in the CMB. According to Lawrence Krauss and Martin White[23], long-wavelength gravitational waves (with

[21]Lawrence Berkeley Laboratory, California, USA. [22]University of California at Los Angeles, USA. [23]Yale University, USA

wavelengths as big as the visible universe itself) would result in a CMB quadrupole anisotropy with a value comparable to that actually measured by COBE. Indeed, the cold dark matter model prediction for the size of the quadrupole, based only on density fluctuations, comes out too low anyway, so, Krauss asserts, it is plausible that some of the quadrupole anisotropy should be due to the gravitational wave background. Future, higher-sensitivity measurements of the CMB, coupled with particle physics experiments searching for supersymmetric particles, may be able to differentiate between the relative influence of gravitational waves and matter-density fluctuations on the CMB.

PHILLIP F. SCHEWE is Chief Science Writer at the American Institute of Physics. He is also the editor of *Physics News*, an annual book, and *Physics News Update*, a weekly digest of physics news items distributed by electronic mail.

Dr Schewe studied physics at the University of Illinois. He received a Doctorate from Michigan State University for his research in high-energy particle physics at the Fermi National Accelerator Laboratory. He has also worked at the Brookhaven National Laboratory.

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CHEMISTRY

Michael Freemantle

The advancement of knowledge in chemistry during the last 20 years has been among the most rapid in the basic sciences, and yet is likely to be proven a mere harbinger of the rate of its development in the early 21st century. The major factor responsible for this burgeoning research effort is the widespread application of discoveries in chemistry as materials or processes that are used in innumerable areas of human activity from *haute cuisine* to the high-technology industries. At current rates, the publication of about 500 000 research papers in chemistry and the granting of roughly 100 000 chemistry-related patents may be anticipated each year.

In order to provide a representative yet concise survey of developments in chemistry from the preceding three years or so, it has been necessary to select topics, based upon several criteria, from the vast body of available information. The first of these criteria is the topicality that follows intense research activity in a given area. There is some consensus among the international community of chemists that certain so-called 'hot spots' in chemistry can be identified by the increasing number of published papers relating to these topics. Such hot spots are to be found in each of the main branches of chemistry: physical, inorganic, organic, analytical and macromolecular. The topics featured in this survey are therefore those that have been the subject of intense research activity. Some, such as the CFCs, superconductors and fullerenes, have also received extensive coverage in the popular press around the world.

The interdisciplinary nature of some of these topics has also been a reason for selection. Chemistry on the atomic scale and the new superconductors, for example, are of interest to both chemists and physicists. CFCs and their alternatives are the focus of much attention not only in pure and applied chemistry but also in the various branches of environmental science. Another example of an interdisciplinary topic included in this survey is molecular electronics. This field of science embraces chemistry, physics, biology, electronics and information technology.

A third consideration in selecting topics has been their potential benefit to humanity. Recent developments in asymmetric synthesis and more specifically the development of chiral drugs are prime examples. If scientists in the early 1960s had had the knowledge of asymmetric synthesis and associated techniques that is now available, disasters such as the thalidomide tragedy may never have occurred. The fullerenes, which offer immense potential in a number of fields including medicine, are another example of a development in chemistry that is likely to benefit humankind.

CHEMISTRY ON AN ATOMIC SCALE

The prospect of manipulating single atoms and building chemical structures atom by atom has, besides exciting the interest of chemists, drawn the attention of material scientists, mineralogists and electronic engineers who foresee a range of potential applications which are likely to lend increased power and refinement to a variety of high technologies. For instance, in the field of study known as nanotechnology, the use of single particles as electronic devices could lead to the development of a new generation of microchip. Indeed some researchers have suggested that in the future it may well be possible to store all the contents of the US Library of Congress on a single silicon disk 30 centimetres in diameter. Another possible application is the production of pocket computers with the memory of one of today's supercomputers. Nanotechnologists envisage the development of atomic-scale sensors that could be implanted inside the human body in order to monitor concentrations of blood constituents. The development of devices that move in the bloodstream and remove occlusions in the arteries or repair brain damage are also predicted. Since the fabrication of such devices presupposes a knowledge of the arrangement and stability of particles in the nuclei of atoms, an intensified research effort has been directed in recent years towards understanding atomic nuclei.

Protons and neutrons, the particles contained in the nucleus of an atom, are collectively known as nucleons. Scientists at the Universities of Birmingham, Oxford and York in the UK have studied the arrangement of nucleons inside the nucleus by using a Nuclear Structure Facility (NSF) that generates beams of nuclei which are accelerated towards a target. The resulting high-energy collisions cause the nuclei to fragment. Study of the decay products of such high-energy collisions using solid state silicon detectors revealed that the nucleons were arranged in clusters. For example, an oxygen atom which has 16 nucleons (and hence the symbol ^{16}O) was split into an alpha particle consisting of four nucleons and a carbon nucleus of 12 nucleons (^{12}C). The magnesium (^{24}Mg) atom underwent symmetric fission to form two ^{12}C nuclei (Figure 1). These clusters of nucleons, which have been termed nuclear molecules, have a lifetime of about 10^{-20} seconds.

In recent decades, research groups at the Lawrence Berkeley Laboratory in California, USA, the Laboratory for Heavy Ion Research in Darmstadt, Germany, and the Laboratory of Nuclear Reactions in Dubna near Moscow, Russia, have been working on the syntheses of trans-uranium elements – those having an atomic number of 93 or more. These groups have used cyclotrons and linear accelerators to bombard an element either with neutrons or with nuclei of other elements. New elements are formed when the bombarding neutrons or nuclei penetrate the target nucleus. Elements with atomic numbers 93 (neptunium) to 100 (fermium) were all synthesized in the 1940s and early 1950s. More recently, elements 101 (mendelevium) to 109 (provisionally named unnilennium) have been made, one atom at a time. Element 108 has been synthesized, for example, by bombarding iron-58 nuclei (atomic number 26) at lead-208 (atomic number 82) to form element 108 (known as unniloctium, symbol Uno):

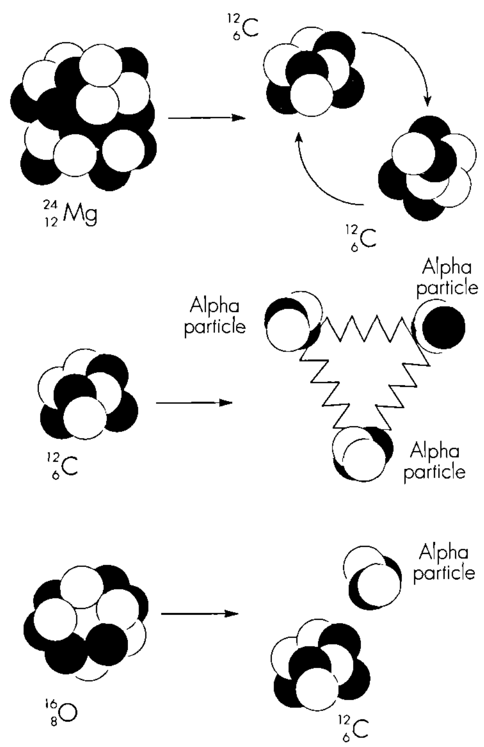
$$^{208}_{82}\text{Pb} + ^{58}_{26}\text{Fe} \rightarrow ^{265}_{108}\text{Uno} + ^{1}_{0}\text{neutron}$$

Such transuranium elements are unstable and become more difficult to synthesize as their atomic numbers increase. Only three atoms of element 109 (unnilennium) have ever been made and each one has survived for a mere 3.4 milliseconds. Detection of a new element is therefore one of the major problems in this type of research. According to Glenn Seaborg, who won the Nobel Prize for Chemistry in 1951, and whose group at Lawrence Berkeley Laboratory has synthesized 10 transuranium elements, improving the sensitivity of detectors is one of the main thrusts of current work.

Rapid advancements have also occurred over recent years in the development and application of devices such as the scanning tunnelling microscope (STM) which enables scientists to examine the surface topography of a material on an atomic scale. The STM uses an electron probe consisting of a metal such as gold or tungsten. The tip of the probe is just a few atoms thick and is brought to within a few atoms distance of the surface. The close proximity of the probe gives rise to a secondary electron emission from the surface of the specimen which can be detected and displayed as an image on a cathode ray screen. As the probe moves over the specimen the latter's surface contours can be visualized on the screen.

Initially the STM was employed in a passive role to produce images of the atoms on the surface of a specimen.

FIGURE 1
CLUSTERS OF NUCLEONS



Magnesium (top) can exist as a nuclear molecule, with two carbon nuclei orbiting each other. Carbon (middle) and oxygen (bottom) can also have a complex structure.

Source: New Scientist, 6 April 1991: 21.

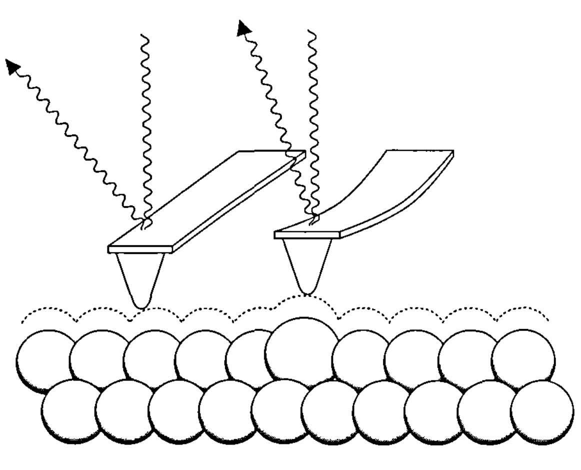
More recently, it has also been used in an active role in the development of atomic-scale electronic devices. New structures on the surface of a specimen can be created by precise manipulation of atoms and molecules with the STM tip. The first example of an active role for STM was reported in 1987 when Becker and colleagues[1] transferred a single atom of germanium from the STM probe tip to a germanium surface by suddenly increasing the top voltage to four volts.

More recently Whitman and co-workers[2] reported the manipulation of atoms and molecules adsorbed on room-temperature surfaces with the use of the electric field produced by an STM tip. The induction of the directional diffusion of caesium atoms adsorbed on the surfaces of semiconductors such as gallium arsenide (GaAs) is an example of such manipulation.

The STM was also used by In-Whan Lyo and Phaedon Avouris[3] for the controlled manipulation of strongly bound silicon atoms or clusters of atoms at the nanometre (10^{-9} m) scale to fabricate new types of electronic devices. Another widely reported use of the STM is in the construction of an atom switch. In such a device the tungsten tip of an STM is kept stationary 0.5 nanometres above a nickel surface. A pit in the nickel contains a single atom of the inert gas xenon. By adjusting the voltage pulse, the xenon atom can be transferred from the nickel surface to the tip and back. The state of the switch (position of the xenon atom) is identified by measuring the conductance across the gap.

A related technique uses an atomic force microscope (AFM) to produce images of atoms on a solid surface by bringing a metal tip into contact with the surface and moving it backwards and forwards (Figure 2). This technique has been employed by Robert Barrett[4] to store quantities of charge in a thin three-layer nitride-oxide-silicon insulator, and could permit the storage of 10 billion bits of information – the equivalent of over 31 000 pages of typescript – on one square centimetre of recording medium.

FIGURE 2
THE ATOMIC FORCE MICROSCOPE



The atomic force microscope senses surface features through deflection of the probe tip on a cantilever beam. Here, light reflected from the cantilever is used to measure this deflection

Source. *Chemistry & Industry*, 21 September 1992. 687

FEMTOSECOND CHEMISTRY

The investigation of the dynamics of elementary chemical reactions and primary photochemical processes using various molecular beam and advanced laser techniques has attracted much interest in recent years. Over the past four decades, it has been possible to detect chemical intermediates with progressively shorter lifetimes. Initially these reactions were measured on a millisecond (10^{-3} s) timescale but gradually the capability to make nanosecond (10^{-9} s) measurements was acquired. With developments in lasers and synchrotron instrumentation it became possible to characterize intermediates with picosecond (10^{-12} s) lifetimes.

In June 1991 Ahmed Zewail and colleagues[5] reported experiments which had enabled them to take 'snapshots' on a femtosecond (10^{-15} s) timescale of the transition states that occur during chemical reactions. In this technique a chemical reaction is initiated by exposing individual molecules from a molecular beam source to an energizing pulse from a laser. The energized intermediates of this reaction are investigated spectroscopically using an electron pulse source as a probe and the resultant electron diffraction pattern is detected using a linear diode array. This technique has been used to study the reaction between hydrogen iodide (HI) and carbon dioxide (CO_2). First, the

[1]AT&T Bell Laboratories, New Jersey, USA. [2]National Institute of Standards and Technology, USA. [3]IBM, Yorktown Heights, NY, USA. [4]Stanford University, California, USA. [5]California Institute of Technology, Pasadena, USA

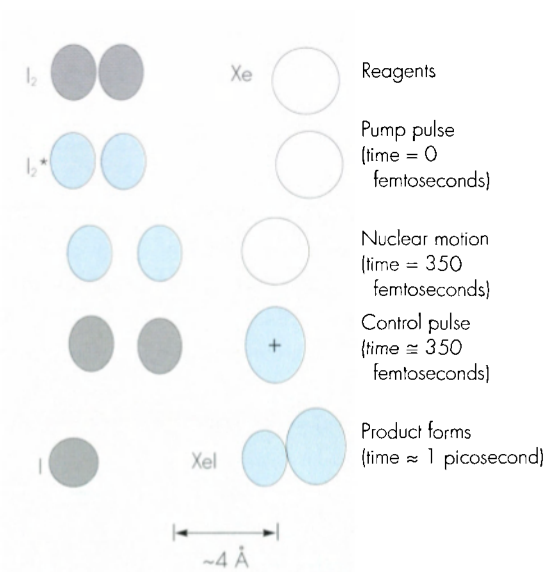
bond between the hydrogen and iodine was broken using the pump pulse. The resulting free hydrogen was found to attack the CO_2, sticking to it for a few hundred femtoseconds. The hydrogen then removed one of the oxygen atoms from the CO_2 and some 5 picoseconds after the start of the reaction, a free hydroxide (OH) species appeared.

In studying the dynamics of elementary reactions the motion of atoms and molecules in general elementary chemical reactions is considered. The following reaction is an example:

$$A + BC \rightarrow [A{\cdot\cdot}B{\cdot\cdot}C]^{\ddagger} \rightarrow AB + C$$

Products AB and C are formed from reactants A and BC after passing through the transition state $[A{\cdot\cdot}B{\cdot\cdot}C]^{\ddagger}$, in an infinitesimally brief time in some reactions. The dynamics of such reactions can be studied because of the current availability of methods such as spectroscopy of transition states and surface aligned photochemistry (SAP). SAP is a rapidly growing field in which single crystals are mounted in an ultrahigh vacuum and coated with less than one monolayer of substrate. The substrate is then irradiated with a laser to induce a photochemical reaction. SAP reactions are thought to be analogous to prebiotic chemistry (chemical reactions that led to the origin of life on Earth), depletion of ozone in the upper atmosphere and the etching of semi-conductors.

FIGURE 3
USING FEMTOSECOND PULSES



A femtosecond pump laser promotes an I_2 molecule to an excited state (I_2*) with an I-I bond length of 2.5 Å (1 angstrom = 10^{-10} m). After 350 femtoseconds, the bond length increases to 4.5 Å. A control pulse is then imposed, resulting in the formation of the product XeI.

Source: *Chemical & Engineering News*, 6 January 1992 7, adapted from *Nature*. Reprinted with permission from *Nature*, 355 (2 January 1992) © Macmillan Magazines Ltd

Femtosecond pulses can be used to influence the course of a reaction during formation and break-up of the *transition state*. Using two sequential coherent laser pulses, the reaction of iodine (I_2) molecules with xenon (Xe) atoms to produce xenon iodide (XeI) can be controlled by exciting the reactants through the transition state $[Xe^{+}{\cdot\cdot}I^{-}{\cdot\cdot}I]^{\ddagger}$ in a two-step process (Figure 3).

$$Xe + I\text{–}I \rightarrow [Xe^{+}{\cdot\cdot}I^{-}{\cdot\cdot}I]^{\ddagger} \rightarrow XeI + I$$

By use of what is termed a switch effect, achieved by varying the time delay between the pulses, scientists are able to turn the formation of the product XeI on or off.

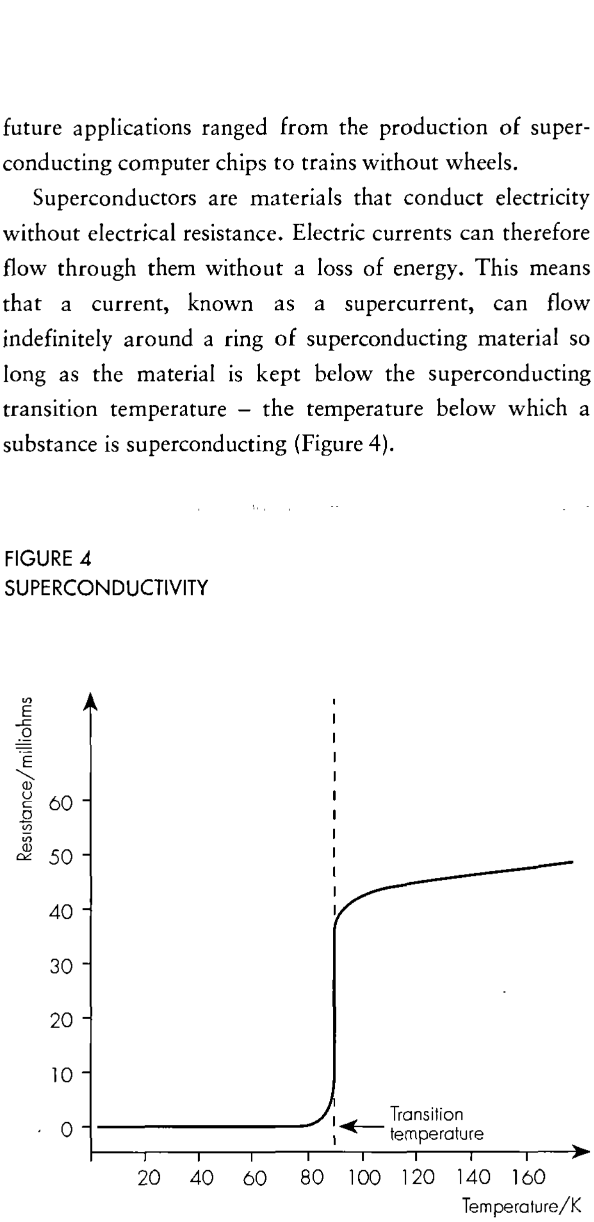
The study of chemical reactions using experiments with a resolution of 10^{-15} seconds could prove to be a revolutionary development in that it may well enable chemists to monitor the movements of single atoms in complex molecules as they rearrange themselves during a reaction. These techniques may also turn out to be powerful tools for scientists in other disciplines; biologists would be able to use them to study the modes of action of enzymes and hormones, and surface scientists to investigate the movement of atoms during heterogeneous catalysis – a process widely used in the manufacture of commonly used chemicals such as ammonia and sulphuric acid.

NEW SUPERCONDUCTING MATERIALS

The discovery of high-temperature superconductors in 1986 sparked an explosion of excitement in the scientific community – among chemists and physicists alike – and in the world's press, and suggestions regarding their possible future applications ranged from the production of superconducting computer chips to trains without wheels.

Superconductors are materials that conduct electricity without electrical resistance. Electric currents can therefore flow through them without a loss of energy. This means that a current, known as a supercurrent, can flow indefinitely around a ring of superconducting material so long as the material is kept below the superconducting transition temperature – the temperature below which a substance is superconducting (Figure 4).

FIGURE 4
SUPERCONDUCTIVITY



When a superconductor is cooled, its electric resistance drops to zero at the transition temperature.

Source: *Impact of science on society* (1989), 154. 134.

Before 1986 the highest transition temperature was 23.3 K – achieved with an alloy of niobium and germanium. Then, in January 1986, Georg Bednorz and Alexander Müller[6] found that a ceramic material containing the elements lanthanum, barium, copper and oxygen conducted currents without resistance at 35 K, a breakthrough which was to earn the authors the 1987 Nobel Prize for Physics. The following year another ceramic material containing yttrium, barium and copper ($YBa_2Cu_3O_7$) – known as a 1-2-3 superconductor – was found to be superconducting at 94 K, a temperature higher than the boiling point of liquid nitrogen (77 K). Before this discovery, liquid helium, which is much more expensive than liquid nitrogen, had been required to cool the alloys to below their transition temperatures.

Superconductors containing copper and oxygen are known as cuprate superconductors and have general formulas such as $YBa_2Cu_3O_{6+x}$, $Nd_{2-x}Ce_xCuO_4$ and $La_{2-x}M_xCuO_4$, where M is a metal such as strontium or barium. These materials have perovskite-related structures (Figure 5) containing CuO_2 planes along which superconductivity takes place. Between these planes are layers of metal and/or metal oxygen; these support the CuO_2 and act as charge reservoirs.

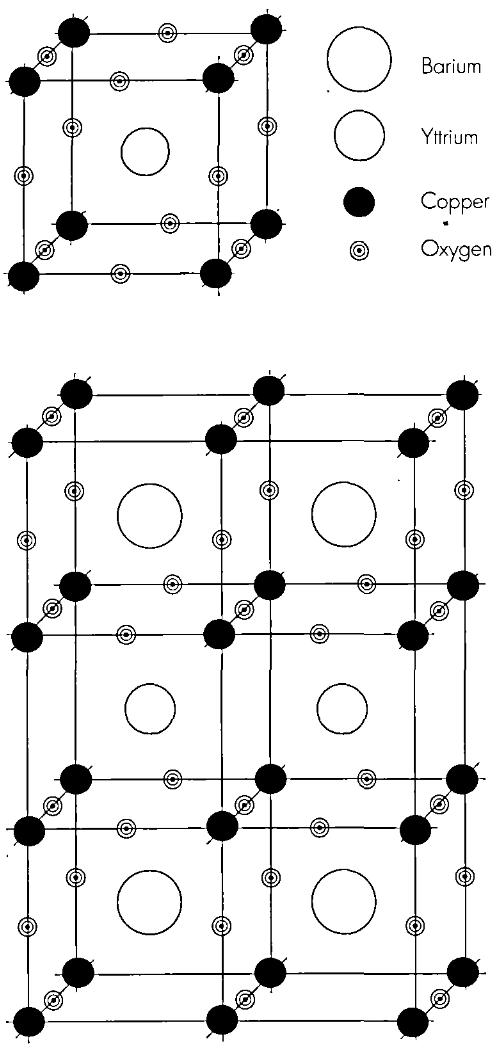
Since 1987 the euphoria induced by these discoveries has subsided somewhat, although the flow of research papers, review articles and news reports on the topic continues unabated. One of the main problems has been that the ceramic superconductors studied are brittle and inflexible and thus unsuitable for use as wires that may need to be wound into coils. Also their critical current density – the amount of electric current they can carry – is limited. More recently some laboratories have reported the successful fabrication of flexible superconducting wire and the first motor using high-temperature superconducting coils that produces a usable power output. The coils are made of a bismuth-based superconductor and operate at the temperature of liquid nitrogen.

High-temperature superconducting quantum interference devices (SQUIDs), which are used to detect minute changes in magnetic fields and electric currents, are now commercially available, as are a range of high-temperature superconducting thin-film filters and thick-film devices including shields and pick-up coils.

Research on the ubiquitous $YBa_2Cu_3O_7$ has continued at full-flow over recent years and according to one report it has been possible to increase the critical current density of this material. Another group of researchers at the Los

[6] IBM Research Laboratory, Rüschlikon, Switzerland

FIGURE 5
SUPERCONDUCTING MATERIALS



A perovskite material has a cubic structure (top) with a large metal atom, such as an yttrium atom, in the centre of the cube and small metal atoms, such as copper atoms, on the corners of the cube. The edges of the cube contain oxygen atoms. The 1-2-3 superconductors have perovskite structures (bottom). However, oxygen atoms are missing from the vertical edges around the yttrium atoms and from some of the horizontal edges around the barium atoms.

Source: *Impact of science on society* (1989), 154: 140.

Alamos National Laboratory in the USA have deposited $YBa_2Cu_3O_7$ as thin films by a technique known as sputtering, which involves bombarding the material with ionized gas molecules inside a vacuum chamber. The film was examined using scanning tunnelling microscopy and atomic force microscopy.

The search for new copper-oxide-based and other types of superconductor has continued. One exciting development has been the discovery of superconductivity below 40 K in an 'all-layer' compound of strontium, neodymium, copper and oxygen. A new family of superconductors containing the element gallium has also been discovered. These have the general formula $LnSr_2Cu_2GaO_7$, where Ln stands for yttrium or any of the 14 lanthanide elements. Superconductivity was observed at 30 K and 73 K in these substances. Peter Edwards and Ru Shi Liu[7], and the Interdisciplinary Research Centre for Superconductivity (Cambridge, UK), have studied thallium-based superconductors with a typical formula $Tl_2Ca_2Ba_2Cu_3O_{10}$. These have transition temperatures up to 128 K, the highest reported to date (late 1992). Some scientists now predict that further experiments on these materials will push transition temperatures up to 180 K or higher.

In 1983, some organic salts containing sulphur were shown to be superconducting at temperatures up to 10.4 K. These organic superconductors have sandwich structures consisting of conducting layers of flat organic molecules separated by insulating layers of inorganic ions. The compound with the formula $K\text{-}(ET)_2Cu[N(CN)_2]Cl$, where ET stands for the organic component bis(ethylenedithiolo)-tetrathiafulvalene, has a transition temperature of 12.8 K – the highest currently (1992) recorded for salts of this type.

In 1991 Arthur F. Hebard, Robert C. Haddon and colleagues[8] demonstrated that the potassium-doped fullerene K_3C_{60} is superconducting at 18 K. A few months later the record transition temperature for fullerenes was pushed up to 33 K by a group led by Kutsumi Tanigaki[9], using the compound Cs_2RbC_{60}. The record has since been increased by a further 10 K (see below).

The synthesis of superconductors with progressively higher transition temperatures is a reflection of the effort being made by scientists in this field to develop materials

[7]University of Birmingham, UK. [8]AT&T Bell Laboratories, New Jersey, USA. [9]NEC Corporation, Japan

which would be superconducting at room temperature. The technical applications of such superconductors promise immense economic benefit. At present, power transmission along supply lines results in significant losses of electricity due to the resistance in conventional cables. High-temperature superconducting cables would almost eliminate this energy loss because they offer no resistance against the electric current. These materials are also good conductors of heat and therefore could be used in the manufacture of miniature computers since they would prevent the accumulation of excessive heat, a problem that is at present preventing the further miniaturization of computer chips.

Currently available superconducting materials are already being used as windings for powerful electromagnets and in linear motors that promote levitation. In fact, they have been used in the construction in Japan of a prototype train which floats on a magnetic field.

FULLERENES

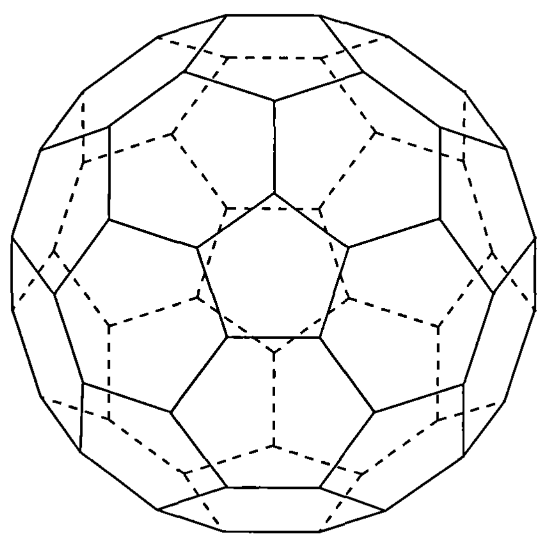
No other topic in chemistry has attracted more attention over the past three years than the fullerenes. In 1992 scientists published about 700 research papers on the fullerenes during the course of the year – that is at the rate of one every 13 hours.

A fullerene molecule has an even number of carbon atoms arranged in a configuration that forms closed, hollow cages. These molecules were first observed in 1984 when it was found that vaporized graphite contained large clusters made up of even numbers of carbon atoms ranging from 40 to 100. The most famous, buckminsterfullerene, with the formula C_{60}, was identified as a particularly stable cluster in the carbon vapour produced by the laser irradiation of graphite, by Richard E. Smalley[10], Harry F. Kroto[11] and co-workers. The 60 carbon atoms of the molecule were found to be arranged as a geodesic network – resembling a soccer ball. C_{60} was named aftet the American architect and inventor Richard Buckminster Fuller whose geodesic dome (first perfected in 1947) encloses a greater volume with a given amount of material than any alternative structure (Figure 6) and has been regarded as the most significant structural innovation of the 20th century.

Although buckminsterfullerene was identified some years ago, it was only prepared in usable macroscopic quantities in 1990, and this development led to the publication of the prodigious number of papers on C_{60} and related molecules such as C_{70} – which has a shape similar to a rugby ball. Among these reports were studies on the X-ray crystal structure of an osmium tetroxide (OsO_4) derivative of C_{60}, the use of the STM (see above) to study the ordered overlayer growth of C_{60} on gallium arsenide and the use of atomic force microscopy (AFM – see above) and X-ray diffractometry to study the topography of C_{60} films on a calcium fluoride substrate.

C_{60} is the simplest of all the fullerenes. All its 60 carbon atoms occupy equivalent positions and therefore its nuclear magnetic resonance (NMR) spectrum has just one peak. C_{70} has five peaks, while C_{76} has 19 peaks. When the preparation of a new type of fullerene structure consisting of hollow graphitic needle-like tubules of nanometre (10^{-9} m) dimensions was reported in 1991 by Sumio Iijima[12] they were promptly dubbed 'buckytubes'.

FIGURE 6
BUCKMINSTERFULLERENE



Source *Chemistry International* (1987), 9(6): 212

[10]Rice University, Houston, Texas, USA. [11]University of Sussex, Brighton, UK. [12]NEC Corporation, Fundamental Research Labs., Japan

The tubules, which are formed of numerous rolled up sheets of carbon atoms in hexagonal arrays, have been used as moulds to draw out metal wires with a diameter of a few nanometres. The synthesis of these tubules in gram quantities was achieved by T.W. Ebbesen and P.M. Ajayan[13] using a standard arc-discharge technique for fullerene synthesis under a helium atmosphere. Robert L. Whetten and colleagues[14], and François Diedrich[15], reported the fusion of C_{60} and C_{70} in hot, dense vapours to form stable higher fullerenes, and large molecules, such as C_{120}, C_{140} and even C_{240}, which are multiples of C_{60} and C_{70}, were identified in the mass spectra of these vapours. Using conventional spectroscopic techniques, C_{60} and C_{70} were identified by a group at MIT, Cambridge, Mass., in samples of condensible compounds and soot collected from the flames produced by burning hydrocarbons, while C_{60} and higher fullerenes were detected by three Australian scientists, Louis S.K. Pang, Anthony Vassallo and Michael A. Wilson, during laser irradiation of brown coal. Macroscopic quantities of these fullerenes have been prepared from coal-derived coke, their identity being verified using an ion cyclotron mass spectrometer. In addition, a number of higher fullerenes, including C_{76}, C_{84}, C_{90} and C_{94}, have been isolated and partially characterized.

Fullerenes C_{60} and C_{70} were reported by Peter R. Buseck and Semeon J. Tsipursky[16] and Robert Hettich[17], occurring naturally in a sample of shungite, a rare carbon-rich rock found near the town of Shunga in Russia. The origin of the rock is uncertain but it is thought to be more than 600 million years old. However, some astrophysical evidence suggests that carbon in its fullerene configuration may not be peculiar to planet Earth; many of the mysterious features in the infrared emission spectra of interstellar matter – believed to originate from carbon-rich material – match fairly well the vibrational spectrum calculation for $C_{60}H_{60}$, the saturated hydride of C_{60}.

The fullerenes are the third form of pure carbon to be identified; graphite and diamond, the other two forms, have been commonly used for centuries. The fullerenes are non-reactive because all the valencies on each of their C atoms are co-valently satisfied and their spherical or near-spherical shapes present no protruding reactive sites for attacking molecules. A C_{60} molecule will only dissociate at a temperature of 3 000 K.

One of the potential applications of the fullerenes might be their use as highly dispersed supports for metal catalysts. It has been found that metals could be attached directly to the carbon framework by the reaction of C_{60} with organometallic ruthenium and platinum reagents. The

TABLE 1
POTENTIAL APPLICATIONS OF FULLERENE C_{60} AND RELATED MOLECULES

CATALYSTS	Fullerene materials could be used as supports for highly dispersed metal catalysts.
SUPERCONDUCTORS	C_{60} doped with alkali metals such as potassium and rubidium can conduct electricity without resistance.
OPTICAL LIMITERS	Fullerenes could be used as optical limiters for protecting optical sensors from intense light.
INDUSTRIAL DIAMONDS	C_{60} can be crushed under high pressure at room temperature to a solid harder than diamond.
CANCER TREATMENT	Antibodies for tumour cells may be attached to the fullerene molecules which are then guided to the tumour.
TAILOR-MADE DRUG-DELIVERY SYSTEMS	Drugs could be incorporated inside the hollow fullerene cages and released inside the body.
MOLECULAR BATTERIES	These might be produced by trapping various atoms inside the fullerene cages.
COMPUTER CHIPS	Ultrathin carbon nanotubes could be used as fibres to replace the copper wires that connect computer chips, resulting in much faster processors.
ROCKET FUELS	Since C_{60} can withstand extreme pressures, it could be used in rocket fuels.
SUPERFIBRES	Carbon fibres used nowadays are very strong. Fullerene nanotube fibres would be far stronger.
LUBRICATION	Fullerene molecules surrounded by fluorine atoms would be extremely stable both chemically and physically. They would make ideal lubricants.

[13]NEC Corporation, Fundamental Research Labs., Japan. [14]University of California, Los Angeles, USA. [15]Federal Technical Institute, Zürich, Switzerland. [16]Arizona State University, USA. [17]Oak Ridge National Laboratory, Tennessee, USA

preparation of lanthanum-containing fullerenes by laser vaporization of a lanthanum oxide/graphite composite rod heated to 1 200 °C in a stream of argon gas has also been accomplished. Another similar development, reported by C.N.R. Rao and his team of chemists[18], was the preparation of a fullerene containing a single transition-metal atom (such as an iron atom) inside its carbon cage by vaporizing graphite in an atmosphere of the compound $Fe(CO)_5$.

A further possible use for the fullerenes was evident when it was discovered by Art Hebard and his colleagues[19] that thin films of the substance doped with a variety of alkali metals (for example, potassium) conducted electricity when isolated from air. Subsequent work revealed that when C_{60} is doped with a small quantity of potassium atoms, the material becomes superconducting (see above) at a temperature of 18 K. Studies aimed at elucidating its crystal structure have revealed that pure samples of alkali-metal fulleride K_3C_{60} consist of a face-centred cubic lattice of C_{60} with potassium atoms occupying all the octahedral and tetrahedral interstices. Even more recently it has been found that C_{60} doped with caesium and rubidium is superconducting at 33 K. It is now known that alkali-metal fulleride superconductivity could be improved by a further 10 K elevation of its transition temperature to 42 K by adding thallium to rubidium- and potassium-doped C_{60}. Sekin and colleagues[20] have observed a further increase in the transition temperature to 57 K. Researchers have also established that C_{60} doped with the organic compound tetrakis(dimethylamino)ethene (TDAE) becomes an organic molecular ferromagnet at 16.1 K.

C_{60} in the solvent toluene has been reacted with xylylene – a compound related to benzene – to form an insoluble brown compound. Using NMR spectroscopy, thermal gravimetric analysis and elemental analysis data, the researchers Douglas A. Loy and Roger A. Assink[21] have shown that this product is probably a copolymer of C_{60} and xylylene in the ratio 1:3.4.

Some unusual optical properties of buckminsterfullerene which could prove potentially useful have also been discovered. Research has shown that photo-excited C_{60} molecules absorb light better than when in their ground state. This property of C_{60} could be used to limit the performance of optical sensors which need optical limiters to protect them from damaging light levels when used with bright sources such as lasers and arc welders.

Buckminsterfullerene molecules, with their highly symmetrical soccer-ball geometry, are extremely stable physically. Even so, a team of researchers in Grenoble, France, reported that they had been able to crush C_{60} to diamond at room temperature by applying high pressures. There have been suggestions that this discovery might lead to a new method of producing industrial diamonds.

CFCs AND THEIR ALTERNATIVES

Chlorofluorocarbons (CFCs) and related chlorine- and bromine-containing compounds have been used extensively over recent decades as refrigerants, aerosol propellants, foam blowing agents, cleaning solvents and in other applications. Until the 1970s these compounds were considered environmentally friendly and highly desirable from an engineering point of view because they were non-toxic, non-flammable, non-volatile, non-corrosive and very stable. For example, CFC-12 (dichlorofluoromethane, CCl_2F_2, also known as FREON-12) was originally considered to be a miraculous refrigerant. It is not surprising then that by the 1970s the world production of CFCs had reached about a million tonnes per year.

Questions about depletion of stratospheric ozone were first asked in the early 1970s, and in 1974 this phenomenon was linked for the first time to the CFCs. Knowing that chlorine radicals are able to catalytically decompose stratospheric ozone, scientists suggested that the main anthropogenic source of chlorine in the stratosphere, the CFCs, could be responsible for depleting the Ozone Layer. They estimated that if the rate of production of CFCs continued unchanged, half a million tonnes of chlorine would accumulate in the stratosphere each year. This, they predicted, would double the natural rate of ozone decomposition and, as a result, would deplete stratospheric ozone by 7-13%.

Chlorine radicals (Cl·) are produced by photolytic dissociation of CFCs in the lower stratosphere. The follow-

[18]Indian Institute of Science, Bangalore, India. [19]AT&T Bell Laboratories, New Jersey, USA. [20]National Research Institute for Metals, Tsukuba, Japan. [21]Sandia National Laboratories, New Mexico, USA

ing reactions for CFC-11 and CFC-12 respectively are typical:

$$CCl_3F + h\nu \rightarrow CCl_2F\cdot + Cl\cdot$$

$$CCl_2F_2 + h\nu \rightarrow CClF_2\cdot + Cl\cdot$$

The Cl· radicals then destroy ozone catalytically at all altitudes in the stratosphere in a series of processes including the following which involve chlorine monoxide (ClO·):

$$Cl\cdot + O_3 \rightarrow ClO\cdot + O_2$$

$$ClO\cdot + O\cdot \rightarrow Cl\cdot + O_2$$

Scientists estimate that a single chlorine radical can react with up to 100 ozone molecules. Moreover, they predict that CFCs, because of their stability, can survive in the stratosphere for up to 100 years.

A group of bromine-containing compounds related to the CFCs and known as halons (CF_2BrCl and $C_2F_4Br_2$) have been used widely in fire extinguishers and are even more destructive. They release bromine radicals (Br·) which form bromine monoxide (BrO·) in reactions similar to those shown above. The concentration of halons in the stratosphere has been increasing at the rate of over 5% per year.

The total stratospheric concentration of chlorine today is about 3 parts per billion (ppb: parts per 10^9 molecules of air). This compares with 0.6 ppb a century ago and 2 ppb in the late 1970s. In the stratosphere, chlorine is present mainly in the form of CFCs and their photochemical by-products such as chlorine monoxide. Bromine, in the form of halons and bromine monoxide, is also present at about 0.02 ppb.

CFCs are also efficient greenhouse gases contributing 15-20% to the thermal blanket around the earth. The greenhouse warming effect of one molecule of CFC-11 or CFC-12 is equivalent to that of 10 000 molecules of CO_2.

Over the past two decades societies throughout the world have become increasingly aware of several forms of global pollution which result in phenomena such as ozone depletion, greenhouse warming, acid rain and chemical smog that in turn could endanger life on Earth.

Based on the accumulation of scientific evidence, national and international agencies began to recognize in the middle 1970s that CFCs might be amongst the major contributing factors to global pollution. In 1976 the Environment Protection Agency (EPA) in the USA announced its intention to prohibit the non-essential use of CFCs as aerosol propellants, but by 1984 production of CFCs worldwide had surpassed their pre-ban levels and exceeded 1 million tonnes annually.

In order to prevent any potentially catastrophic effect on the biosphere as a result of further depletion of the stratospheric ozone layer, on 16 September 1987, 24 nations signed the Montreal Protocol produced under the auspices of the United Nations Environment Programme (UNEP). The following were the three main requirements of the Protocol:

The 1986 levels of consumption of CFCs-11, -12, -113, -114 and -115 must not be exceeded after mid-1989.

The 1986 levels of production must be reduced by 20%

NOBEL PRIZES

The 1992 Nobel Prize for Chemistry was won by **Rudolph A. Marcus** who is Arthur A. Noyes Professor of Chemistry at the California Institute of Technology. The Prize was awarded for his contributions to the theory of electron-transfer reactions in chemical systems. His theory helps to explain a wide range of phenomena, including the fixation of light energy by green plants, chemiluminescence, electrochemical synthesis and analysis, corrosion, electrically conducting polymers and the photochemical production of fuel.

Physical chemist **Richard Ernst** of the Eidgenössische Technische Hochschule (ETH) in Zürich, Switzerland, was awarded the 1991 Nobel Prize for Chemistry for his research work on magnetic resonance. Nuclear magnetic resonance (NMR) spectroscopy is used routinely in chemistry departments around the world to analyse the structures of materials. Ernst greatly increased the sensitivity of the technique and pioneered a two-dimensional version, enabling its application to much larger molecules than before. Ernst's discoveries also led to an entirely new scheme for obtaining medical images of the human body by magnetic resonance. This technique can detect tumours and may well supersede the use of X-ray scanners in the diagnosis of cancer.

from 1 July 1993 and an additional 30% (bringing the total to 50%) by I July 1998.

A freeze at 1986 levels of consumption of halons by 1994.

TABLE 2
OZONE DEPLETION POTENTIALS (ODPs) AND GLOBAL WARMING POTENTIALS (GWPs) OF CFCs, HCFCs AND HFCs

Compound	Formula	ODP (relative to CFC-11 = 1.0)	GWP (relative to CFC-11 = 1.0)
CFC-11	CCl_3F	1.00	1.0
CFC-12	CCl_2F_2	1.00	2.8 - 3.4
CFC-113	CCl_2FCClF_2	0.80	1.4
CFC-114	$CClF_2CClF_2$	1.00	3.7 - 4.1
CFC-115	$CClF_2CF_3$	0.60	7.5 - 7.6
HCFC-22	$CHClF_2$	0.05	0.34 - 0.37
HCFC-123	$CHCl_2CF_3$	0.02	0.017 - 0.020
HCFC-124	$CHClFCF_3$	0.02	0.092 - 0.10
HCFC-141b	CH_3CCl_2F	0.10	0.087 - 0.097
HCFC-142b	CH_3CClF_2	0.06	0.34 - 0.39
HFC-125	CHF_2CF_3	0	0.51 - 0.65
HFC-134a	CH_2FCF_3	0	0.25 - 0.29
HFC-152a	CH_3CHF	0	0.026 - 0.033

More nations agreed to the Protocol at international ozone conferences held in London in March 1989, attended by representatives from 123 countries, and in Helsinki in May 1989. In 1990, hydrochlorofluorocarbons (HCFCs) – manufactured as alternatives to CFCs – were introduced into the Protocol as transitional substances.

With the production of CFCs and related compounds scheduled to decline dramatically over the next decade or so, CFC producers have been investing heavily in the development and testing of environmentally friendly CFC substitutes and alternative technologies which will meet the needs of society. However, it is recognized that in many cases – in refrigeration and air-conditioning equipment for example – large reductions in emissions, particularly in the short term, can be made simply by recovering and recycling CFCs during servicing.

Several companies are involved in the development of activated carbon systems for the recovery of CFCs used as blowing agents in plastic foam manufacturing processes. The systems are expensive but may be able to recover 40% of the blowing agents. According to some industrialists it is likely that conservation of CFCs and utilization of alternative products or technologies will reduce demand for CFCs by up to 60%. This will leave about 40% of the current market open to substitution by alternatives to CFCs – a quantity of perhaps 500 000 tonnes per year.

It is perhaps an irony that stability, the very factor which made CFCs so important, now makes them a threat to the environment. Reduced atmospheric stability can be achieved by the presence of hydrogen in the molecule which allows the compound to be degraded by hydroxyl (OH·) radicals. Partially halogenated methane and ethane compounds – all containing hydrogen – have been developed and are now being manufactured on a large scale. These are the HCFCs, but they still contribute to ozone depletion although less so than CFCs (Table 2). Much industrial research and development is now being devoted to finding new routes to ozone-friendly compounds such as the hydrofluorocarbons (HFCs) which do not contain chlorine or bromine. The capacity for a CFC or HCFC to destroy ozone depends on the amount of chlorine it contains and also its lifetime in the atmosphere. Ozone depletion potentials (ODPs) measure the contribution of various CFCs and their possible replacements towards degrading ozone relative to CFC-11, which is given a value of 1.0. Global warming potentials (GWPs) have been calculated using computer models and are also relative to CFC-11, which is assigned a value of 1.0 for this property as well. Some of the values quoted in recent reports are shown in Table 2.

In January 1988, a Programme for Alternative Fluorocarbon Toxicity Testing (PAFT) was established to evaluate the safety of suitable CFC alternatives. The results of the acute, sub-acute and sub-chronic studies together with *in vitro* mutagenicity and teratogenicity tests on HCFC-123, HFC-134a and HCFC-141b indicated that the toxicity profiles of these three compounds are very similar in many respects to CFCs-11 and -12. The combined two-year chronic/carcinogenicity assays on these products are currently ongoing, with publication expected in the near future. Reports of the results of studies on HCFC-124 and HFC-125 are expected in 1994-95.

The 1987 Montreal Protocol and its subsequent amendments were revised at a meeting of the world's environment ministers in Copenhagen, Denmark, in November 1992 and further decreases in the production and use of CFCs and related compounds compared to levels in 1986 were imposed (Table 3).

TABLE 3
REVISED MONTREAL PROTOCOL DEADLINES IMPOSED AT COPENHAGEN IN NOVEMBER 1992

Compounds	Uses	First cutback Year	%	Phase-out Year
CFCs	Aerosols, refrigeration, air-conditioning, cleaning, foams	1994	75	1996
HCFCs	CFCs substitutes	1996	cap	2030
Halons	Fire extinguishers			1994
CCl_4	Solvent	1995	85	1996
CH_3CHCl_3	Solvent	1994	50	1996
CH_3Br	Fumigant	1995	cap	not set

The Copenhagen meeting also extended the restrictions on HCFCs which were introduced into the Montreal Protocol in 1990 as transitional substances: as from 1996 their usage will be capped at 1989 levels plus 3.1%. Thereafter, the use of HCFCs will be progressively reduced: 35% by the year 2004; 65% by 2010; 90% by 2015; 99.5% by 2020 and 100% by 2030.

Methyl bromide, CH_3Br, which is used as a fumigant to kill pests in soil and stored fruit crops, was added to the Protocol at Copenhagen. In 1995, production will be frozen at 1991 levels, with reductions to be considered at a later stage.

ORGANIC SYNTHESIS

The broad nature of the branch of chemistry commonly referred to as organic synthesis was exemplified by the 600 or so papers presented at the 9th International Conference on Organic Synthesis, held in Montreal, Canada, in July 1992, where expositions were given on the syntheses of a diverse range of organic compounds including amino acids, carbohydrate derivatives, antibiotics, polyaromatic compounds, esters, celluloses, organometallic compounds, antiviral compounds, vitamins, antitumour agents and alcohols. In particular, the amount of research on the design and development of new chemical molecules for the treatment, cure or prevention of human and animal diseases is vast. This was evident not only at the Montreal conference but also from the 400 or so papers presented in the section on 'Chemistry and biochemistry of biologically active organic compounds' at the 33rd IUPAC Congress held in Budapest in August 1991.

Among the reports of recently synthesized compounds with therapeutic value were those relating to sesbanimide A and manzanmine A, which are two alkaloids possessing novel structures and antitumour activity; a novel anti-asthma drug called MK-679 or Verlukast; compounds containing the guanidine group; the identification, purification, mechanism of action and synthesis of anaesthetic receptors; studies on insulin and the insulin receptor; the development of a peptide anticoagulant which could be used clinically for the treatment and prevention of thrombosis.

Much recent research has focused on asymmetric synthesis and in particular the synthesis of enantiomeric drugs which are also known as chiral drugs. Enantiomerism or chirality occurs when a molecule is asymmetric and can therefore exist in two forms, each of which is a mirror image of the other. A pair of enantiomers is physically and chemically alike except that they exhibit different optical properties.

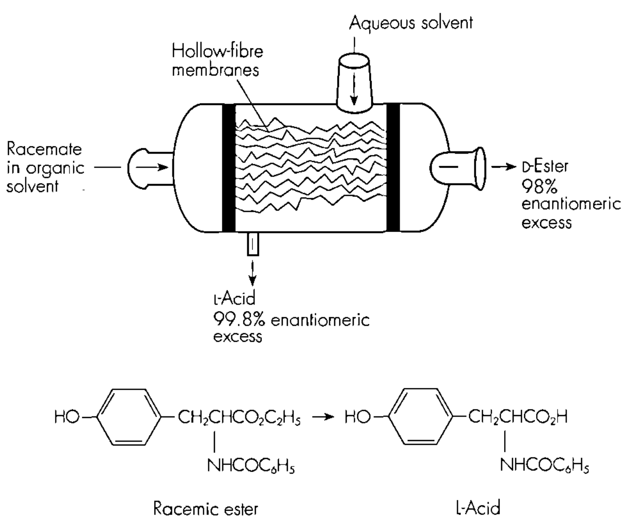
One of the carbon atoms in most amino acid molecules is asymmetric. These amino acids are therefore chiral and optically active, as are carbohydrates such as glucose and other monosaccharides. Chirality is of crucial importance in biological systems; enzymes and most of the compounds they act on are optically active and enantioselective. For example, animals are able to metabolize and yeasts are able to ferment only one of the two glucose enantiomers.

The asymmetric or enantioselective synthesis of bioactive compounds, particularly medicinal drugs, has therefore attracted much interest in chemistry departments in recent years. Unfortunately, conventional methods of organic synthesis of optically active compounds result in racemic mixtures or mixtures of equal quantities of the optically opposite forms.

A recent research report outlined current and potential methods of producing chiral drugs for diseases affecting the cardiovascular system, the genito-urinary system, the central nervous system and the respiratory system. Methods were also described for the stereo specific production of anti-inflammatory drugs and analgesics; anticancer drugs, antibiotics, anti-infectives and anti-virals; hormones; antihistamines and cough and cold medicines.

One procedure for the production of such chiral drugs uses immobilized enantioselective enzymes in hollow-fibre membrane reactors to resolve racemic mixtures (Figure 7). When a solution of a racemic mixture in an organic solvent flows through the reactor the enzyme hydrolyses one of the enantiomers but not the other. The hydrolysed enantiomer is washed away in the aqueous phase leaving the desired enantiomer in the organic solvent.

FIGURE 7
HOLLOW-FIBRE MEMBRANE REACTORS RESOLVE RACEMIC MIXTURES CONTINUOUSLY



Source: Sepracor, in *Chemical & Engineering News*, 28 September 1992: 56.

Chemists have also devised techniques for the preparation, in high yield and high enantiomeric excess, of substituted alkenes which are promising for the commercial production of enantiomeric drugs, pesticides, pheromones (chemical compounds secreted by animals which influence the behaviour of other animals generally of the same species) and flavour and fragrance compounds.

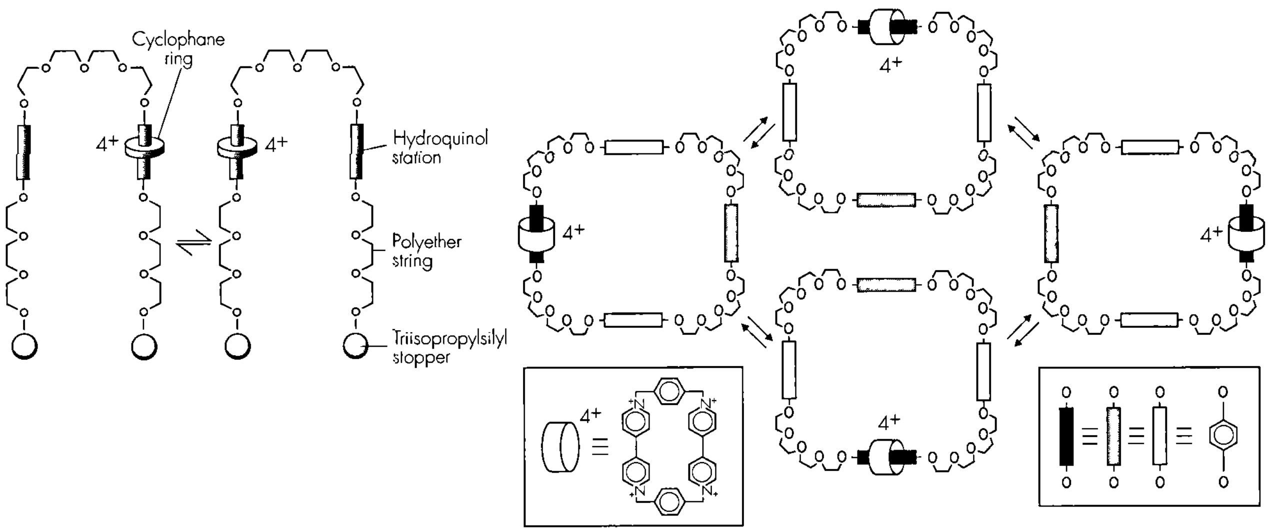
The synthesis of self-replicating molecules has also generated much excitement and interest recently. Experiments have shown that non-enzymatic replication may be possible in a wide range of synthetic chemical systems and are providing clues on how physics and chemistry interacted in the prebiotic evolution systems that existed about 4 billion years ago. This work may also be a step towards the synthetic constitution of primordial living systems. The growth of interest in molecular replication stems from earlier work on the double-helical structure of deoxyribonucleic acid (DNA) and the mechanisms of nucleic acid replication. Research on prebiotic chemistry has now begun to focus on the possible role of simpler replicating polymers which may have been the precursors of the nucleic acids.

Self-assembly and self-replication may be the secrets that synthetic chemists have to learn from nature to be able to construct molecular electronic devices. The generation of supramolecular architecture and machines capable of various mechanical and electronic tasks will depend on understanding and applying the phenomenon of molecular recognition. This involves the spontaneous interaction between host and guest molecules resulting in the self-organization and self-assembly of supramolecular structures. The research effort in supramolecular chemistry is intense; in fact some national research councils have singled this area out as meriting particular attention and support.

In a remarkable feat of organic synthesis, Fraser Stoddart and co-workers[22] have designed a self-assembling molecular shuttle which consists of a ring-shaped molecule that encircles a molecular string somewhat like a bead and switches between two stations on the string. This work could be the first step towards information processing on a molecular scale – the eventual aim being to synthesize

[22]University of Sheffield, UK

FIGURE 8
MOLECULAR SHUTTLES



Molecular shuttles: (left) With the [2]rotaxane system, the ring shuttles back and forth between two stations on the string. (right) With the [2]catenane system, the ring moves around the circle from station to station like a molecular train set.

Source: (left) Bradley, D. How to make a molecular shuttle, *New Scientist*, 27 July 1991: 20; (right) Stoddart, F. Making molecules to order, Scheme 6, *Chemistry in Britain*, August 1991: 717.

controllable molecular-scale computers that can receive, store and transmit information.

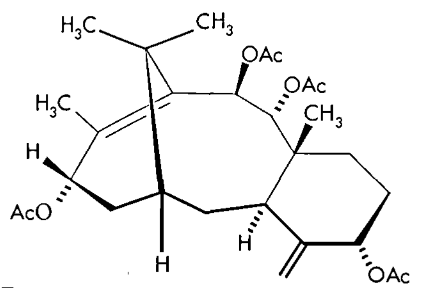
The bead in the molecular shuttle consists of a charged cyclophane ring made up of two bipyridinium residues (Figure 8). The bead moves between two hydroquinol stations positioned symmetrically along a polyether string. The structure is called [2]rotaxane and is prepared by self-assembly from the two molecular components – the string and the bead. In a self-assembly process, a complex product is made in a single step whereas in normal synthesis many steps are required.

Using NMR spectroscopy, it has been established that the cyclophane ring shuttles between the two stations several hundred times per second at room temperature and also that the shuttle needs about 13 kilojoules per mole to do this – far less energy than is required for most chemical reactions.

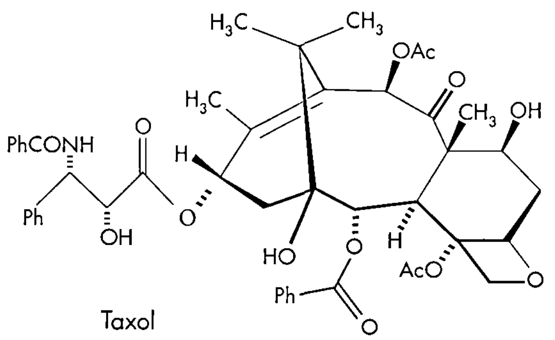
Another type of molecular shuttle has been dubbed a molecular train set running around the circle line. This system consists of two interlocking rings and is known as [2]catenane. One ring, corresponding to the bead, runs around the other ring, which has four hydroquinol stations.

One of the principal aims of chemistry today is to synthesize and develop active molecules and molecular systems which can function electronically, in switching, information storage and logic. The molecular shuttle is an example of a molecular switching system with potential applications in electronics.

TAXOL: A NATURALLY OCCURRING ANTICANCER DRUG



Taxusin



Taxol

Source. *Chemistry International* (1993), 15(1) 9.

In recent years extensive research activity has been devoted to the synthesis of anticancer drugs such as taxol. Clinical trials of this natural product have shown promising results in the fight against a variety of cancers including ovarian, breast and lung cancers. However, testing sponsored by the National Cancer Institute in the USA has been slowed down by the shortage of taxol, and this has prompted chemists and other scientists to intensify research activity to increase availability of the drug.

At present, taxol can only be obtained by extraction from the bark of the Pacific yew tree – a limited resource found in old forests in the Pacific north-west region of the USA which is also the habitat of the endangered spotted owl. Efforts are now underway to meet the growing demand for the drug by total and partial synthesis, leaf extractions, tissue culture and cultivation.

The structurally complex, biologically active taxanes fall into two broadly definable classes: taxusin and taxol (see figure, left). Taxols feature a characteristic hydroxyl (-OH) substituent compared with the taxusins.

A scaled-up version of a patented laboratory semisynthesis of taxol has been developed by Robert A. Holton and colleagues at Florida State University. The chemical process starts with a taxol precursor, 10-deacetylbaccatin III (10-DAB III) which is found in yew needles and twigs – both renewable resources. Production by this process is planned to commence in 1993. In 1994, the company producing taxol by this method plans to obtain 10-DAB III and even taxol directly by extraction from cultivated plants grown from genetically selected stocks.

MICHAEL FREEMANTLE is the Information Officer for the International Union of Pure and Applied Chemistry (IUPAC) in Oxford. He edits the IUPAC news magazine *Chemistry International*, and is responsible for the IUPAC Affiliate Membership Programme.

Dr Freemantle was Lecturer in Physical Chemistry at the Polytechnic of the South Bank, London and Associate Professor of Physical Chemistry at the University of Jordan in Amman. He has worked as an editorial consultant in science education for UNESCO and has also written eight books on science, including *Chemistry in Action*.

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BIOLOGY

Peter Newmark

Perhaps the most exciting feature of modern biological research is the way in which studies in one area can unexpectedly have consequences for another. Increasingly often, for example, a substance that is discovered because of its activity in one system, is later found with a different activity in a completely different system. This may be because, as more and more of the components of cells and tissues are identified, the chances of finding a completely new one diminish. Or perhaps it reflects the fact that evolution is much more an adaptive than a revolutionary process. Whatever the reason, the outcome is that traditional compartments in the study of biology have broken down to a large extent. What has not changed, however, is that it is frequently the invention of new techniques or the speeding up of old ones that drives the process of discovery.

All five topics discussed in this chapter have made rapid progress because of technical developments, but their inclusion is based on other considerations. Protein structures represent an interface between physics, chemistry and biology: physics provides the crucial techniques, chemistry explains how the structures are held in their three-dimensional shape, and illuminates the biological function of the protein. The study of signal transduction is not only an extremely active area of research but is the key to understanding how external factors can control internal events in a cell, including the degree of activity of the genes in the cell nucleus. The next two topics owe their inclusion to the ever-growing power of techniques of gene manipulation. Gene 'knock-out' is a new technique that is proving immensely powerful in understanding gene function and in creating models of human genetic disease on which to test possible therapies, including gene therapy. Gene 'add-ons' are much less new but, in the case of plants, are just reaching the stage of becoming commercially valuable. Finally, a little space is devoted to an area of immunology that has recently yielded several of its well-kept secrets, shedding much light on one of the most important actions of the immune system – the recognition by lymphocytes of cells that are infected by pathogens.

STRUCTURES

Determination of the three-dimensional structure of proteins and other biological macromolecules is technically very demanding but scientifically very important. Without a three-dimensional structure much guesswork and argument can go into trying to understand the mode of action of a protein. With a structure, most of the guesswork and, often, all of the argument can be eliminated. From 1957, when the first three-dimensional protein structure was worked out, until 1989, around 500 structures were described. But such is the pace of development in the chemical, physical and computing technologies that underlie protein structure determination that another 500 new structures have been reported in the past three years. Pundits estimate that this will increase to 20 000 by the turn of the century. The knowledge is important in many areas: for example, it is helpful in understanding the regulation of genes, the action of enzymes, the way in which hormones deliver messages to cells, the working of the immune system and, increasingly, in drug design.

Traditionally, the method for solving the three-dimensional structure of a protein is that of X-ray crystallography – a combination of low and high technologies. The first requirement, and usually the most frustrating, is the production of a good quality crystal of the protein. Whereas there has been much progress in methods of producing the large quantities of pure protein that are needed before crystallization can be attempted, finding the right conditions for crystals to be formed is still very much a matter of trial and error. It can frequently take months or even years to obtain a sufficiently good crystal for the next stage, in which X-rays are fired at the crystal in various orientations. It is from the diffraction pattern of the X-rays that have passed through the crystal that the three-dimensional arrangement of the atoms in the protein molecule can be worked out. This is by no means a simple process, but it has been greatly speeded up by developments in the technology and computing processes involved.

The rate at which protein structures are solved has also been speeded up by the recent introduction of a sophisticated form of nuclear magnetic resonance as an alternative to X-ray crystallography for solving structures. The new technique is still technically demanding, but as it is applied to a solution of the protein, it avoids the problems of obtaining crystals. On the other hand, unlike X-ray crystallography, nuclear magnetic resonance can only be used for relatively small proteins. There had been some question of how similar the structures of proteins in solution and in crystals would be, but a number of direct comparisons have now shown that they are essentially the same.

One area of biological research that has benefited greatly from advances in structure determination is that of gene regulation. It has been known for many years that proteins are the 'hands' that operate the 'switches' that turn genes on and off. The switches are short pieces of DNA close to the genes that they operate and both the nucleotide sequence of the DNA switch and the amino acid sequence of the protein hand that operates it are known in many cases. But this one-dimensional information is of rather little use in understanding precisely how a switch is turned on or off, because the mechanism involves a three-dimensional interaction between the double helix of the DNA and the folded protein. Three-dimensional structures of several complexes of protein and DNA have now been solved, allowing a detailed understanding of how they interact to operate the switches. (See Figure I, colour section p. vii.) This is only a start, however, for most of these structures are confined to the 'fingers' of the protein hand and the 'tip' of the switch; in the future, the complete structures will be visualized.

There are other vital interactions between proteins and DNA that are very important to understand and that are beginning to be seen in three dimensions. For example, the complex processes of DNA transcription and replication each require several proteins and enzymes that form a variety of complexes as the mechanisms proceed. Three-dimensional structures of some of the individual components have recently been determined. For example, one of the several sub-units of an enzyme central to bacterial DNA replication has been revealed as a protein that is doughnut shaped. The hole in the doughnut is the right size to accommodate the double helix of DNA. This is consistent with the idea, derived from biochemical experiments, that the enzyme acts as a sliding clamp on the DNA.

RNA transcription and AIDS

Another much studied enzyme that interacts with nucleic acids is reverse transcriptase. This enzyme produces DNA from an RNA template whereas, in the usual process of transcription, a messenger RNA is produced from a DNA template. Reverse transcription has been intensively studied because it is the way in which the human immunodeficiency virus (HIV) incorporates itself into human cells. Because the HIV genome is made of RNA it cannot be incorporated into human DNA directly but must first be converted into the equivalent DNA form. As the reverse

NOBEL PRIZES

Nobel prizes are the most valuable and most noticed of the many annual attempts to recognize and award the greatest achievements in science and medicine. They are flawed because no more than three people each year can share any one Nobel prize, despite the fact that great achievements often depend on many individual contributions. And yet they help, however briefly, to increase the public visibility and status of the scientific enterprise. So, bearing in mind that there are many other highly deserving individuals who might have become Nobel Laureates in the past two years, here are some of those whose contributions to the life sciences have been rewarded.

Two German physiologists shared the 1991 Nobel Prize in Physiology or Medicine for their development of a new technique for studying the flow of ions that underlies many biological processes. Ions cross biological membranes by means of membrane proteins that form pores that open and shut. When **Erwin Neher** and **Bert Sakmann** decided to try and measure the flow of ions through a single channel, physiologists still could only look at populations of channels. Since their successful development of 'patch clamping', in which a tiny area of membrane was tightly sealed to the end of a minute pipette linked to electronic measuring devices, it has become relatively easy to measure ion flow through single channels.

The great importance of the discovery of kinases – enzymes that add a phosphate group to other enzymes and thereby activate them – was recognized by the award of the 1992 Nobel Prize in Physiology or Medicine to US biochemists, **Edwin Krebs** and **Edmond Fisher**. They identified a kinase involved in muscle action but hundreds of kinases involved in a huge variety of metabolic processes have since been found.

transcriptase that performs this function is an enzyme of HIV, but not of humans, it is an ideal target for drugs against AIDS. Indeed, AZT, the original AIDS drug, is an inhibitor of reverse transcriptase, as are most of the other prospective anti-AIDS drugs.

Not surprisingly, therefore, there has been a very determined effort to elucidate the three-dimensional structure of reverse transcriptase. After many failures to obtain sufficiently good crystals, the structure was finally solved in 1992 by Professor Tom Steitz and his colleagues[1]. The structure was revealing both to those whose main interest is in how the enzyme works – it acts both to synthesize DNA on the RNA template and to degrade the initial RNA template – and to those whose main concern is the production of better drugs against AIDS. With a precise understanding of the three-dimensional interactions involved in reverse transcriptase functions it should, in theory, be possible to design and synthesize drugs that inhibit these functions in a highly effective manner. If the theory can be put into practice, the result should be drugs that are more efficient and have fewer side effects than, for example, AZT.

Similar reasoning has accounted for intense interest in the structure of other HIV proteins. One in particular is the HIV protease, an enzyme that the virus uses to produce some of its components from larger precursors. The successful determination of the three-dimensional structure of HIV protease by X-ray crystallographers has been followed by fervent attempts to use the structural information to design drugs that inhibit the enzyme. It is estimated that there are now at least 100 three-dimensional structures of complexes of possible drugs with the protease enzyme, although many of these have not seen the light of day as they have been determined within pharmaceutical companies who keep them hidden, at least for a time, from their rivals. For all that, so far no really promising drugs have emerged.

Cell receptors

Another important area of recent achievement in structure studies concerns the receptors that are embedded in the surface membranes of cells and that serve as sensors of chemical ligands in the environment. In the case of single-celled organisms, the ligands may, for example, be foodstuffs towards which the organisms swim; in the case of multicellular organisms, the ligands are commonly hormones or growth factors that are carried in the bloodstream or other fluids of the body to their target cells or organs. Again, pharmaceutical scientists are interested in these structures because they are excellent targets for drugs. But there is also a great deal of fundamental interest in understanding the ways in which the interaction between receptors, which are usually proteins, and their ligands, some of which are also proteins, leads to biochemical and behavioural changes in the cells that carry the receptors. The intracellular changes that follow this process of signal transduction have been extensively documented, but how they are triggered in the first place will not be understood without structural information of the type that is just beginning to emerge.

A very big hurdle in determining the three-dimensional structure of receptors is that their natural state is to be partially embedded in a membrane that has a high lipid content. It is very difficult to extract them intact from these membranes into solution either for study by nuclear magnetic resonance or for crystallization purposes. Fortunately, the ligand-binding parts of receptors are not within the membrane but protrude from its outer surface, and these parts seem to behave much like soluble proteins. The structures of the ligand-binding parts of two receptors were first worked out during 1992. One is the receptor for the amino acid, aspartate, on the surface of certain bacteria: the outcome of aspartate binding is that the bacterium moves towards the source of the aspartate. This structure was solved by Professor Sung-Hou Kim and his colleagues[2]. The other is the human growth hormone receptor, which was worked out by a team led by Dr Tony Kossiakoff[3]. In each case, structures were obtained of the receptor, both on its own and bound to its ligand. This produced the first solid information of the kind of changes that occur in receptor structure as a result of ligand binding.

One very important result from these studies is the first clear picture of how a single molecule of a ligand can bind to two molecules of its receptor. (See Figure J, colour section p. viii.) Obviously, two different surfaces of the

[1]Yale University, USA. [2]University of California, Berkeley, USA. [3]Genentech, California, USA

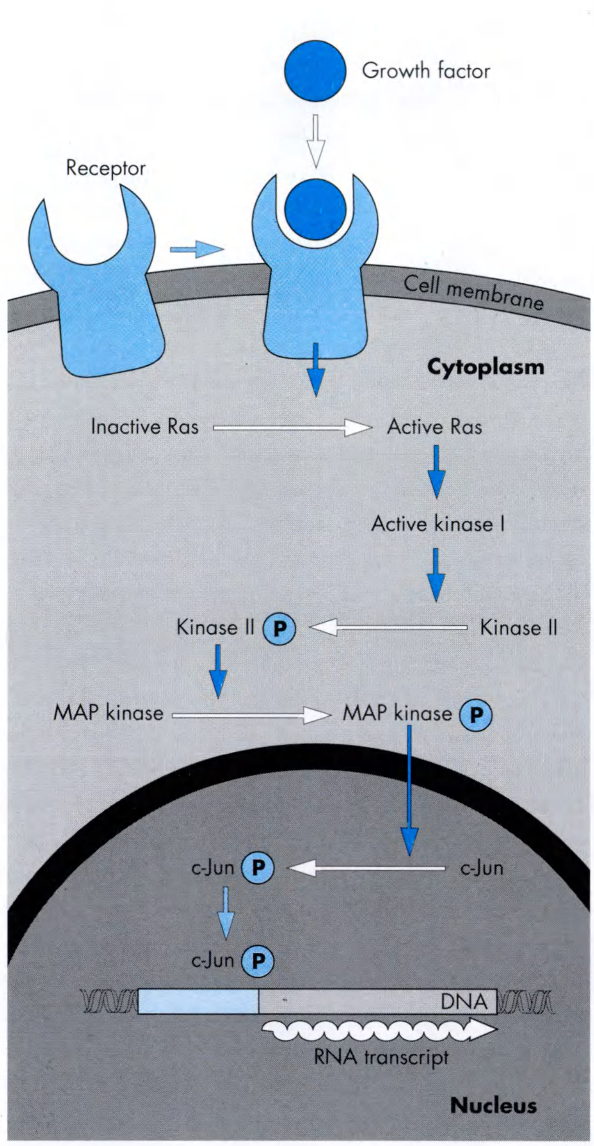
ligand, human growth hormone, are involved but, surprisingly, there is very little obvious difference between the sites to which they bind on the two receptor molecules. Although pairs of receptor molecules weakly associate in the absence of the hormone, their pairing is strongly promoted by its presence. This pairing is responsible for the transduction of the hormone signal to the interior of the cell. In all likelihood, it results in structural alterations to those parts of the two receptor molecules that lie either within the membrane or, more importantly, on the inside of the cell. But we shall have to wait and see because, for reasons already explained, the structure that has been determined is only that part of the receptor that is outside the cell.

SIGNALS

Whatever exact types of structural alterations to the intracellular portion of receptors result from ligands binding to the extracellular portion, the immediate outcome is the triggering of events within the cell. Knowledge of these events, collectively known as signal transduction, has grown both incrementally and conceptually in the past few years. The intense recent interest in signal transduction owes much to the fact that disruption in any of its steps can contribute to the formation of malignant tumours. Evidence continues to mount that cancer is frequently associated with mutations in the genes that encode the proteins involved in signal transduction. It is likely that mutations in several genes are necessary.

An overriding concept is that many of the events in signal transduction involve the addition of phosphate groups to proteins or their removal, changes that activate or de-activate the functions of the proteins. This concept is an old one and there has long been evidence for the existence and function of the kinase enzymes that add phosphates to proteins during signal transduction. Indeed, in many cases, the portions of receptors that are inside cells themselves have a kinase activity that is turned on when a ligand binds to the extracellular portion of the receptor. More recently, many of the phosphatase enzymes that remove phosphates from proteins have been identified.

FIGURE 1
A CASCADE OF KINASES



The engagement of a growth factor with its receptor on the surface membrane of a cell can set in motion a series of events within the cell cytoplasm, including a succession of phosphorylations by kinase enzymes that culminates in gene transcription in the cell nucleus. Ⓟ represents a phosphate group.

Two other related avenues of research have been particularly revealing. First, much has recently been learnt about a type of protein that links the interior portion of activated receptors to other proteins as part of the signal transduction process. The linking proteins can vary greatly in many respects but all are characterized by one feature – the presence of what has become known as an SH2 domain, which is essential for the link. The receptors that are linked to their partners by SH2-containing proteins are invariably those whose intracellular portion has a kinase function; the partners are one of a variety of enzymes that function to pass the signal towards its endpoint.

The other avenue of research has revealed a whole cascade of phosphorylating enzymes that tentatively link ligand-binding on the cell surface to the endpoint of many forms of signal transduction, the switching off or switching on of gene transcription. One example that is relatively well characterized involves a cascade of three kinases, which is set in motion when a growth factor binds to its receptor on the cell surface (Figure 1). The receptor is itself a kinase, and an early outcome of its activation is the activation in turn of a protein known as Ras. This seems somehow to trigger the first of the kinases in the cascade to phosphorylate and thereby activate the second, which then does the same to the third or MAP kinase. Finally, MAP kinase phosphorylates a protein named c-Jun which is part of a complex that binds to certain genes and switches them on. One major contributor to this field of research is Professor Edwin Krebs[4], who was awarded a Nobel Prize in 1992 for his pioneering contributions to the study of protein phosphorylation (see p. 224). There is growing evidence for the operation of very similar cascades in cells from other organisms, ranging from yeast to mammals. By now there is little doubt that this kind of mechanism has been conserved in evolution and has been adapted to function in the transduction of a wide variety of signals to an equally wide variety of endpoints.

GENE KNOCK-OUTS

A great deal of biological understanding has traditionally come from the study of mutant organisms. These are the result of chance mutations that have occurred either spontaneously – that is, without human intervention – or in the presence of mutagenic agents. Recently, however, techniques have been developed that essentially remove the element of chance and allow one to mutate any chosen gene. The techniques were pioneered in simple organisms, but gene 'knock-out', as it is usually called, is now possible in the common experimental animals and in plants. The standard technique (Figure 2) that has evolved for mice is first to achieve the gene knock-out in a cell taken from a very early mouse embryo and then to put the cell with the knocked-out gene into another very early mouse embryo, from which a fully grown chimaeric mouse develops. In such a mouse, many of the cells, including some germ cells (the sperm or eggs, depending on the sex of the mouse) will lack the gene. This is unlikely to have any serious effects on the mouse itself but by breeding the chimaeric mice it is possible to obtain offspring in which both copies of the gene are missing in all the tissues; these mice will demonstrate the full effects of the gene knock-out.

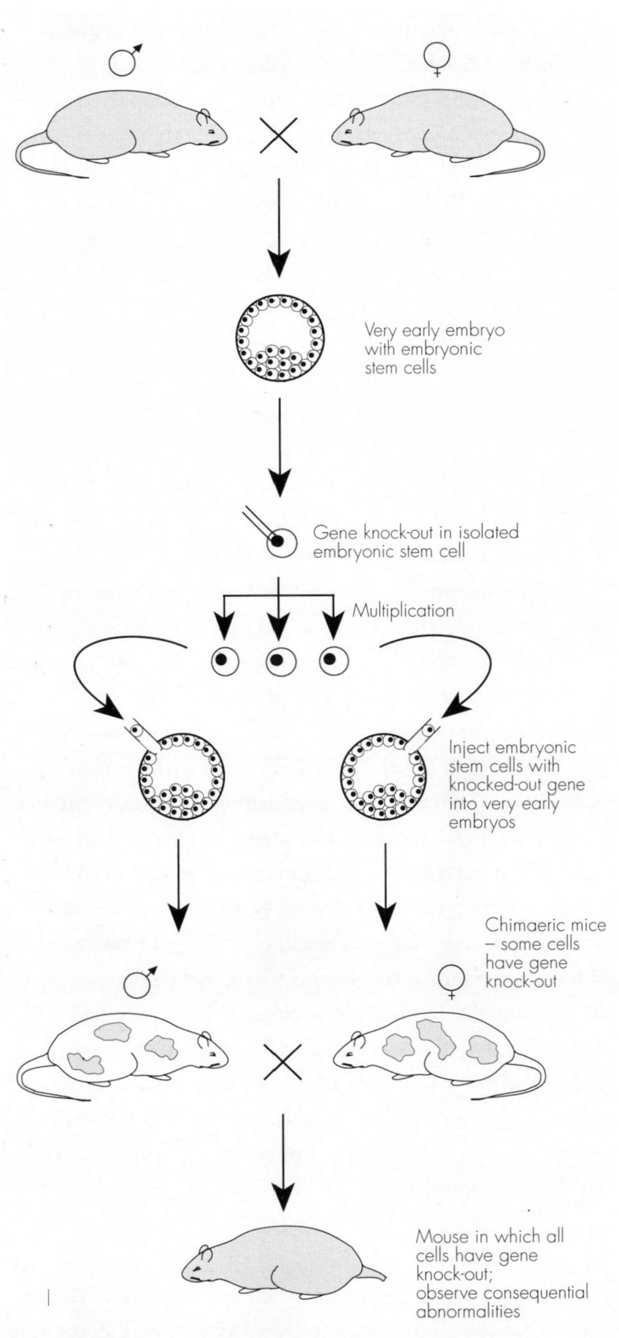
Gene knock-out technology has two major uses. The first is to create animal models of human diseases that are caused by an inherited gene mutation. The second is to try to establish the function of a gene.

One recent example of an attempt to establish gene function by gene knock-out will illustrate why the technique is needed and what kind of information is obtained. Studies of the fruit fly, *Drosophila*, had identified a number of genes that are involved in determining the highly segmented nature of the fly's body. One of these genes is named *wingless* because in its absence flies develop without wings. When a gene similar to *wingless* was subsequently identified in mice on the basis of similarities in DNA sequence, the question was what was the so-called *Wnt-1* gene doing in mice? The first clues came from examining in which mouse tissues and at what stage the gene was turned on. The clear-cut answer was that it is active only in specific regions of the developing central nervous system. But, unfortunately, this provided few clues as to the actual function of the *Wnt-1* protein produced by the gene.

Far more of a clue came when Dr Andy MacMahon and colleagues[5] analysed the development of the central nervous system in knock-out mice that were missing the

[4]Washington University, Seattle, USA. [5]Roche Institute of Molecular Biology, Nutley, New Jersey, USA

FIGURE 2
A SCHEMATIC ILLUSTRATION OF THE WAY IN WHICH GENE KNOCK-OUT ANIMALS ARE PRODUCED



Wnt-1 gene. The result is that embryonic offspring, in which both *Wnt-1* genes are missing, have severe abnormalities in parts of the developing central nervous system, and adults have symptoms that suggest defective cerebellar function. Not all the regions in which the normal gene is active in the developing central nervous system seem to be abnormal in its absence, suggesting that in some regions other genes can substitute for the missing *Wnt-1*. Sometimes attempts to establish gene function are thwarted either because the missing gene is so important that organisms without it die as embryos, making it difficult to study the gene's function in detail, or because, as we have just explained, other genes are available to take over from the missing gene. One reason is that many back-up systems have evolved precisely to protect against the loss of a vital gene. This has become increasingly evident in experiments where a gene that encodes an important protein is experimentally inactivated or even deleted from a cell. The expected outcome is that the cell will not be able to survive; the actual outcome, in some cases, is that the cell has little, if any, problem. As it is inconceivable that the protein has no function in the cell, the most likely explanation is that another protein takes over the function.

Gene knock-out, once thought to be beyond the realms of experimental possibility, has become an almost standard technique in mice during the past few years. It will be a very powerful way of obtaining some evidence of the type of function of a gene that has been discovered simply by sequencing DNA, as is increasingly the case. Note, however, that it still cannot provide precise information on the function of the gene. Thus, the fact that mice lacking the *Wnt-1* gene have central nervous system abnormalities in itself does little more than to narrow the possibilities. Other evidence suggests that the protein is some kind of signalling molecule that is secreted from the cells that produce it and delivered to other cells. But the gene knock-out experiments cannot easily test such suppositions.

Their value is more precise when gene knock-out is used to produce an animal model of disease, allowing potential forms of therapy to be tested. For example, once the gene that is mutated in persons with cystic fibrosis had been precisely identified, it was possible to knock out the equivalent gene in mice. These animals have many, but not all, of the features of young patients with cystic fibrosis: their intestinal tracts are obstructed, there are pathological changes in the respiratory tract, and their lifespan is greatly shortened. Another example of the production of an animal model of human disease by gene knock-out has come from inactivating the gene for an enzyme called glucocerebrosidase. Defects in this gene in humans cause Gaucher's disease, the most prevalent of a group of diseases in which substances that are normally degraded by enzymes instead accumulate in lysosomes. The most severely affected of the children who inherit defective glucocerebrosidase genes die of neurological disease shortly after birth; mice with inactivated glucocerebrosidase genes have a number of symptoms consistent with nervous system dysfunction and die within a day of birth.

The most radical form of experimental treatment that can be tested in animals with a defective gene is gene therapy, in which the animals are provided with a fully functioning version of the knocked-out gene. Generally, the aim is to put this version of the gene into the cells or tissue that are most seriously affected by its absence – for example, muscle in muscular dystrophy or epithelial cells in cystic fibrosis. Very recently Dr Christopher Higgins[6], together with colleagues in Oxford and elsewhere in the UK, showed that gene therapy will cure at least some of the symptoms of the mice with a cystic fibrosis-like disease caused by gene knock-out. Therapy was achieved by delivering a specially constructed version of the human gene into the trachea of the mice, with the aim of encouraging the incorporation of the gene into the cells of the respiratory tract and the lungs. Evidence was obtained that the gene had been incorporated and was functioning. More importantly, the abnormal chloride transport in the epithelial cells of the mice was restored to normal. As these abnormalities are very similar to those that are the major cause of early death in cystic fibrosis patients, there is considerable optimism that this type of gene therapy might also help patients with cystic fibrosis. Such tests have already been approved, and are being carried out. But the first highly experimental attempts at gene therapy of a disease of children involved a very few cases of adenosine deaminase deficiency. This fatal, but very rare, enzyme deficiency is the result of inherited defects in the gene for adenosine deaminase. The major consequence is that the immune system of these patients is severely defective. Attempts are under way to test whether placing a functional version of the gene in the circulating blood cells of patients will produce sufficient quantities of the enzyme to restore a reasonably effective immune system.

Gene maps

The obvious prerequisite for any form of gene therapy is the availability of the gene. And yet in many diseases that are the result in whole or in part of genetic defects or variations, the gene or genes involved have not been isolated. Even where there is no thought of gene therapy but it is simply a case of wanting to discover the cause of a genetic disease, the most direct approach is to identify the defective gene or genes. This need, among others, has led to the highly ambitious plan of sequencing the complete human genome and thereby finding all the genes, even though they constitute only a small part of the total DNA.

A complementary, and much less demanding, plan is to 'map' the whole human genome. A complete genetic map would make it a relatively simple matter to identify genes that are associated with diseases, because it provides a series of reference markers that precisely guide the hunt for an unknown gene. The markers need to be in a specific order along each of the chromosomes, whose DNA constitutes the complete genome, and there needs to be a defined distance between each pair of markers. The shorter the distance between pairs of markers, the more precisely is the hunt for a gene narrowed.

The identification of a new and powerful series of markers in 1989 has greatly increased the quality of genetic maps, such that in 1992 a map of 800 markers on the human genome was produced by Jean Weissenbach and co-workers[7]. Even so, the distance between these markers is the equivalent of 5-10 million bases of DNA, making the identification of a single gene a formidable task. However, maps with markers that are only 1-2 million bases apart are already in the offing. When they become available, the task of analysing human diseases

[6]Institute of Molecular Medicine, Oxford University, UK. [7]Genethon, Paris, France

that are under the control of several different genes, such as diabetes and hypertension, should become much easier.

GENE ADD-ONS TO PLANTS

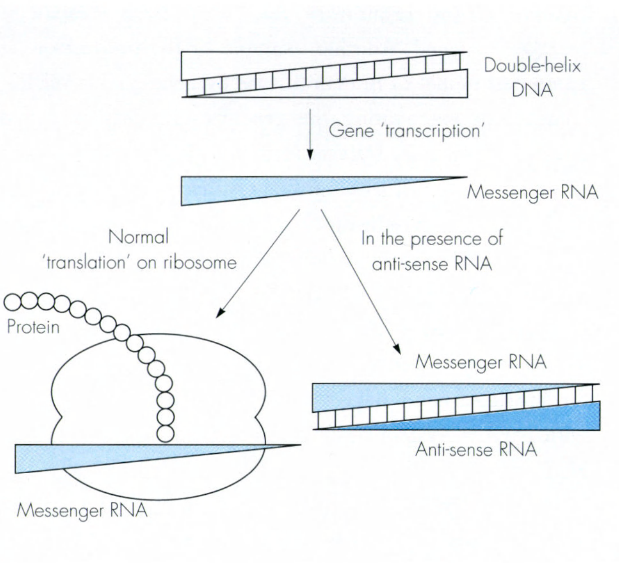
Gene mapping and manipulation is as active a pursuit among plant geneticists as among those who study humans and other mammals. In plants, the most important form of manipulation is gene 'add-on', an older and simpler technique than gene knock-out. Whereas removing a gene requires precise targeting of that gene – the rough equivalent of finding a needle in a haystack – adding an extra gene is much less demanding because precise targeting is not needed when adding an extra gene to the chromosomes of a plant (or animal). The technique has been used both to explore gene function and to create 'useful' variants. Undoubtedly, its most important use in the past few years has been to alter plants for the benefit of biotechnology companies, plant breeders and, sometimes, humankind.

Probably the most commercially advanced plant with an extra gene is the tomato. Ripe tomatoes are soft and easily damaged. Consequently, if they have to be transported far, they are frequently harvested when green and hard. Although such tomatoes ripen and turn red after picking, their fruit quality and flavour is no match for tomatoes ripened on the plant. A related problem is that it is not long before ripe tomatoes become over-ripe and unpalatable – that is, they do not have a long enough shelf life.

Plant biotechnologists have therefore been seeking ways to alter tomato plants so that their fruits can ripen longer before being harvested and, once ripe, last longer before becoming unpalatable. Their aim has been to understand the enzymes involved in ripening and then to provide the plants with additional genes that enable the ripening processes to be modified. Several different approaches have been taken, the most advanced of which should lead to sales of the 'Flavr-Savr' tomato in the United States during 1993.

One of the enzymes involved in tomato ripening is polygalacturonase. Like any other enzyme or protein, polygalacturonase is synthesized according to the instructions carried by messenger RNA from the gene to the ribosome. In theory, at least, this process can be inhibited by hijacking the messenger; scientifically, messenger RNA is best hijacked by causing it to pair up with complementary or 'anti-sense' RNA (Figure 3). Functionally, the result is equivalent to a gene knock-out although the effect is not so absolute. Plant biotechnologists have learnt how to synthesize genes that will produce anti-sense RNA and how to make them function in plants. 'Flavr-Savr' tomato plants contain an added gene for an anti-sense RNA that pairs with polygalacturonase RNA, inhibiting production of the enzyme. As a result, says the US biotechnology company that has developed them, the tomatoes can be left to ripen longer on the plant and have an improved flavour.

FIGURE 3
MODIFYING GENE FUNCTION



The way in which anti-sense RNA prevents gene function; the messenger RNA that carries instructions from the gene to the site of protein synthesis in the cell is hijacked by the anti-sense RNA.

GENE THERAPY AND BIO-ETHICS

All radically new clinical procedures tend to raise ethical issues, but gene therapy has raised more than most. In part this is because it is so different from other procedures. But the added factor is that the aims of gene therapy cannot be wholly divorced from eugenics, the study of the possible improvement of the human stock by encouraging breeding of those presumed to have desirable genes. In the hands of some advocates of eugenics, this has also meant the suppression or extermination of those who were presumed to have less desirable genes.

To consider the ethics of gene therapy, as presently conceived, it is best to distinguish somatic cell gene therapy from germline gene therapy. The big difference is that whereas the former is concerned only with trying to correct the defect in an individual suffering from a genetic disease, germline gene therapy would affect not only an individual but his or her descendants.

So far, it is only somatic gene therapy that is being attempted and there is a consensus that, in general, this is ethically acceptable. The first tentative tests are in patients who are seriously ill with a life-threatening disease for which no other effective treatment is available. That, in itself, makes an ethical decision relatively easy. However, it is likely that somatic gene therapy will become more widely used for less threatening diseases. Even so, the aim of the therapy will be no more than to improve the life expectancy and quality of life of the patient, just as with any other form of therapy. Therefore, as long as it is a safe procedure, with no serious side effects, there will be no serious ethical objections to it. One objection is sometimes raised in cases where, for technical reasons, an antibiotic-resistant gene is introduced at the same time as the gene being used for therapy. While this technique is used, there is a chance that it will contribute to the spread of antibiotic resistance in general. This is clearly an ethical issue, but in the light of the many more certain ways in which antibiotic resistance is spread, it is a minor one and will be removed as soon as the technology can be replaced.

With germline therapy, the ethical issues are much more problematic. The medical aim of germline therapy is less to treat the genetic disease in an individual than to prevent its occurrence by correcting or overcoming the genetic defects in spermatozoa, eggs or embryos. In theory, this has the added advantage that the defects will not be passed on to future generations. But that also raises serious ethical problems.

The problems arise precisely because germline gene therapy affects not just an individual but future generations, and in an essentially irreversible way. One ethical problem is whether we have any 'right' to alter the genetic make-up of future generations. Another is that germline gene therapy will have to operate without the informed consent of the patient to the procedure, thus violating one of the basic concepts of medical practice. It is true that parental informed consent can substitute for that of a patient in the case of a child, but with germline gene therapy the decision would be made before, or very shortly after conception and, of course, would apply not just to the offspring but to all descendants.

If one could guarantee that germline therapy would have no unforeseen long-term side effects or other undesirable consequences, there would probably be much less ethical concern about its application to potentially serious diseases. Side effects are certainly a possibility while gene therapy consists of adding a 'good' gene in order to circumvent the problem of the defective gene, because the process of gene addition is an inexact one, with undoubted potential for long-term side effects. However, when reliable techniques become available for replacing the defective gene by a 'good' copy, the possible dangers will be much reduced.

A more fundamental ethical problem will arise with any attempt to use germline therapy to provide 'desirable' characteristics in humans, rather than to prevent disease. For example, parents of short stature might want to add an extra gene for growth hormone to their germline so that their children and grandchildren are of more normal height. Or, if a gene is ever identified that increases intelligence, there may be widespread demand to include an extra copy in the germline. It is understandable that most potential parents want their children and future generations to be at least 'normal', and in some respects above average, but many people would argue that the definition of 'normal' is arbitrary and that variation is very important to the human race. Moreover, height and, even more so, intelligence are the complex consequence of both genetic and environmental factors, making it very much harder to foresee the outcome of any germline gene therapy. The ethics of attempting to alter the natural genetic make-up of the human race for reasons other than the prevention of serious diseases are therefore highly controversial.

A second successful target for anti-sense RNA in tomatoes is the messenger RNA for an enzyme involved in the synthesis of ethylene, which plays an important part in the natural ripening process. Professor Don Grierson's laboratory[8] has shown that this approach significantly delays ripening. Another approach that has been successfully used to inhibit ethylene production is the add-on to tomatoes of a bacterial gene that encodes an enzyme which destroys one of the intermediates in ethylene synthesis in the plants. Tomatoes from these plants are firmer than ordinary tomatoes for at least an extra six weeks.

Improving the flavour of supermarket tomatoes may seem a relatively trivial achievement for plant genetic engineering but, where firm tomatoes go, other plants will soon follow. Resistance to pathogenic insects, viruses and microbes are more generally desirable properties that biotechnologists are trying to engineer into plants by gene add-on. One aim is to add a gene from the bacterium *Bacillus thuringiensis* to plants so that they can then produce a bacterial compound that has long been known to be toxic to insects. Indeed, the *Bacillus* toxin itself is already widely applied to crops as an insecticide. But this would no longer be necessary if the crop plants, themselves, produced the toxin in sufficient amounts to be effective. This can be difficult to achieve but, fortunately, slight modification of the bacterial gene has recently been found to increase greatly the quantity of toxin produced by plants that carry it. Some field tests of plants that contain the bacterial toxin have already demonstrated the hoped-for resistance to insect feeding, and cotton is likely to be the first crop to be commercialized with built-in insect resistance.

The most explored kind of gene add-on for increasing the ability of plants to resist viral infection involves providing the plants with a gene from the virus itself. This is because plants that are themselves producing the protein of the viral coat are less readily infected by the virus. Pioneered in tobacco plants, which become resistant to tobacco mosaic virus, the technique has been shown to be widely successful, most recently, for example, in creating papaya plants with increased resistance to papaya ringspot virus.

Another type of gene add-on modifies plants so that they are resistant to many different types of microbial pathogens. In this case, the idea is first to find the plant genes that are naturally switched on to defend plants against the presence of pathogens, and then to add to the plant extra modified copies of these genes. The modification may, for example, ensure that the protective protein is produced continually rather than just when the plant is under attack, or it may ensure that the quantity of protective protein produced in response to an attack is much greater then normal. This type of technique is only now emerging from the laboratory into field trials.

Whereas tomato, tobacco and potato have been the plants in which most gene add-on techniques have been pioneered, more important targets have been the world's major cereal plants, such as rice, wheat and corn/maize. Success with these plants has lagged behind because the techniques developed for adding genes to other plants did not work well in these crop plants, so other techniques had to be developed. In the most successful method so far, the genes are delivered directly to embryonic crop plant tissue, either by firing DNA-containing micro-projectiles into embryonic cells or by electrically or osmotically 'shocking' protoplasts so that they become permeable to DNA. In either case the new gene becomes incorporated into some of the cells, and plants regenerated from these cells will carry the new gene. Rice yielded to this type of technique in 1988, corn/maize in 1990 and wheat, finally, in 1992. Once the techniques are in place, the addition of potentially useful genes to these plants is rapidly tested. For example, Dr Michael Koziel and colleagues[9] have already published evidence that the addition of the gene from *Bacillus thuringiensis* to maize provides the plants with increased resistance to being eaten by the European corn borer, a major pest in North America and Europe.

Relatively few plants with add-on genes are yet being grown outside the laboratory. In part this is because of concerns about the possibility that the added genes could pass into closely related wild plants by cross-fertilization, and may be unwelcome there for a number of reasons. Regulations have therefore been developed in most

[8]University of Nottingham, UK. [9]CIBA-GEIGY Agricultural Biotechnology Research Unit, North Carolina, USA

countries to make sure that plants with added genes are not grown outside until they have been carefully tested in the laboratory and that large-scale planting outside is not allowed until small-scale trials have been completed and approved. A second source of delay is that it is necessary to be certain that the addition of a gene to a plant does not have any deleterious effects on the plant itself: thus, it would be of little value if rice plants that had been made highly resistant to pathogens produced only half the normal yield of rice. Nevertheless, it is estimated that over 400 field tests of genetically modified plants were carried out in 1992, largely in North America, Europe and China, and it cannot be long before some of these plants are in common use.

They will be followed by many others as genetic engineering is used to modify the chemical composition of plants in order to increase their value in one way or another. For example, plant starches are used in both the chemical and food industries, and both the quality and the quantity of the starch obtainable from plants affect their value. A number of the genes for enzymes that play a part in starch biosynthesis have now been isolated and a start has been made on producing plants in which the genes are inhibited or modified, or to which genes from either plants or bacteria have been added. Parallel experiments have begun to vary the oil composition of plant seeds. In one case an anti-sense RNA approach has been used to increase dramatically the stearate content of rape seed oil. In other gene add-on procedures that point the way to the future, plants have been converted into 'factories' for producing medically or industrially useful compounds that are not of plant origin. Thus plants provided with a pair of bacterial genes that are needed to produce a form of a natural polymeric material, which finds commercial use as a biodegradable plastic, can themselves produce small quantities of similar polymers. And plants containing genes derived from cells of the mammalian immune system can manufacture antibodies.

It should be mentioned that, whilst plant breeders have long been in the business of 'improving' the genetic make-up of their favourite species, their adoption of the techniques of genetic engineering has produced considerable opposition for various reasons.

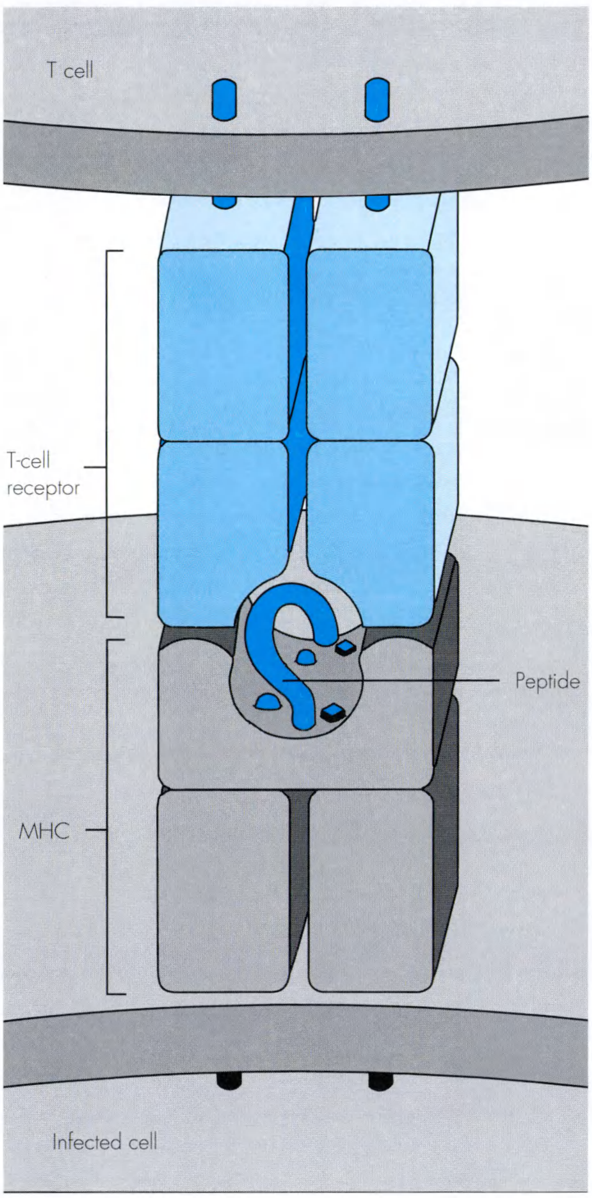
The first concerns were related to the safety of the procedures, especially as the genes being added to one species were more often than not taken from another. This concern led to the development of safety procedures that have since been relaxed as many of the early concerns were found to be largely groundless.

Recently, the concerns have been more about perceived than real problems with the procedure and its results. The case of the 'Flavr Savr' tomato, mentioned above, will illustrate this. Since consumers are likely to welcome tastier tomatoes, as long as the price is not too much higher than less tasty tomatoes, why is there a battle over the acceptability of the plants in the USA? The problem seems to be that genuine concern about the more extreme uses to which genetic engineering could be put has led to an ill-informed public concern about genetically engineered food. Food manufacturers and shops are under pressure from consumer groups to ban, or at least label such foods, and they would rather ignore the facts than risk a loss of business. The more sophisticated argument against the 'Flavr-Savr' tomato is that it still contains a marker gene used in the process of incorporating the gene that affects ripening, and that the marker gene might spread to other species and might also reduce the effectiveness of a human antibiotic. Even if these possibilities can be effectively ruled out, it seems unlikely that the somewhat irrational opposition to genetically engineered foods could be so readily quelled.

ANTIGEN PROCESSING

Antibodies are a vital product of the immune system because they recognize and lead to the removal of foreign substances in the body, and are thus partially responsible for limiting the actions of pathogens. Effective though they are in many circumstances, they are not much use when it comes to eliminating cells that have been infected by pathogens. For that purpose the immune system generates cells that can recognize and kill the infected cells. The recognition process involves an interaction of molecules on the surfaces of the immune cells and the infected cells, and a great deal has recently been learnt about this interaction and the events that make it possible.

FIGURE 4
PEPTIDE RECOGNITION



A highly schematic illustration of the interaction between a T-cell receptor on the surface of a T cell and a peptide that is anchored in position on an MHC molecule on the surface of a pathogen-infected cell.

The immune cells that participate in this process are called T cells (because they derive from the thymus), and the molecules on their surface that are most intimately involved in recognizing the infected cells are the T-cell receptors. What they recognize are fragments of the pathogens' proteins (Figure 4). The fragments – peptides of around 10 amino acids – emerge on to the surface of infected cells anchored to the surface of the major histocompatibility complex or MHC proteins (the full name of these proteins refers to their discovery as the proteins that need to be well matched between individuals if tissue or organ grafts are not to be rejected).

Knowledge of the size and identity of the peptides anchored in complex with MHC has recently been obtained by Dr Hans-Georg Rammensee and colleagues[10] by means of extremely sensitive analysis of the peptides that can be chemically released from highly purified MHC molecules. This kind of information has shown that some of the amino acids are similar in all the peptides, indicating that they are involved in anchoring the peptides to the MHC, whereas others are much more variable. Another great advance in understanding came when scientists led by Drs Pamela Bjorkman and Don Wiley[11] produced the first clear three-dimensional structures of complexes of MHC and peptide, showing that the short peptides fit neatly into a groove on the surface of the MHC molecule. It is this groove that 'faces' the T-cell receptor, and allows the direct contact between the receptor, peptide and MHC that is central to the recognition process.

How do the peptide fragments of the pathogen inside a cell come to be on the surface in a complex with MHC? This question has generated much research and a growing, but still incomplete, understanding of the many processes involved. The most important discovery has been that there are two different routes by which peptides reach the surface, corresponding to the existence of two different types of MHC molecules, known as class I and class II. The reason for this divide is related to the two major places within the cell where proteins from pathogens tend to be found.

Particularly in the case of viruses that use the infected cell's own machinery for making more viral proteins, these

[10]Max Planck Institute, Germany. [11]Harvard University, USA

proteins are present in the cell cytoplasm where they are fragmented into peptides. Some of these peptides are transported into the cell's endoplasmic reticulum, where they form a complex with MHC class I molecules that are ready and waiting. Once the complex is formed, it is transferred to the outside of the cell. Other pathogens, including those that cause leprosy and tuberculosis, either replicate or are degraded in intracellular vesicles of cells. In either case some of their proteins are fragmented into peptides in these vesicles, and are picked up by MHC class II molecules that are passing through the vesicles on their way to the cell surface.

The recognition by a T-cell receptor of a particular peptide-MHC complex is a highly specific one, in that the receptor comes in very many different forms and only those T cells that have precisely the right form for recognizing the particular complex are activated. However, a very different form of interaction between a T-cell receptor, an MHC class II molecule and a molecule from a pathogen has recently come to light. In this case, it is the intact protein, rather than a peptide fragment, of the pathogen that is involved. And the protein interacts with the surfaces of the receptor and MHC molecules rather than fitting into the MHC groove. The best known of this type of protein is the toxin from staphylococcal bacteria that causes toxic shock syndrome. These proteins are known as superantigens because they activate very large numbers of T cells, unlike peptide fragments. Functionally, the outcome of the two types of activation is also very different: whereas peptides activate T cells to destroy infected cells, the activation of T cells by superantigens is part of the mechanism whereby the pathogens that produce them are able to delay or avoid destruction. Thus T cells activated by superantigens may produce compounds that suppress the immune response to pathogens and may become more susceptible to infection by these pathogens.

Many lines of research into possible therapeutic modulation of the immune system have been opened up by the growth of knowledge in the processes involved in T-cell recognition and activation of pathogenic proteins and peptides. But it will take time before it is known whether any practical forms of therapy will emerge.

PROSPECTS

It has only been possible in this article to highlight some of the more striking areas of growth in biological sciences in the past three years. Some other areas of considerable importance have not been discussed, but could well be set for very rapid growth. One such area is neurobiology. In fact, there has been no shortage of descriptive work, identifying the ever-growing list of molecules and their receptors that are involved in the process of transmitting messages between neurons. Now, there are signs that much of this information can be used fruitfully in understanding the regulation of the neuronal circuits and the neuronal basis of learning and memory. Furthermore it can be used to design more sophisticated drugs for the treatment of mental diseases than are presently available. Developmental biology is also about to enter an exponential growth phase. Some of the basic principles that are involved in the very early stages of development, such as the specification of the basic body plan, have been extensively explored in simple organisms like the fruit fly. As it is fast becoming clear that many of these principles apply also to vertebrates, information from any one system is aiding others, and the study of development is set to explode.

PETER NEWMARK is Editor of *Current Biology* and Managing Director of Current Biology Ltd. For 16 years he was on the editorial staff of *Nature* as Biology Editor and later as Deputy Editor.

Dr Newmark received his undergraduate and postgraduate training at the University of Oxford and spent some years as a postdoctoral research scientist at St Bartholomew's Hospital Medical College, London.

FURTHER READING

Structures

Receptor structures are reviewed by Wayne Hendrickson in *Current Biology*, 2(2) (February 1992): 57-9.

Signals

Part of the signalling process is the subject of the article by Maurice Linder and Alfred G. Gilman on G proteins in *Scientific American*, July 1992: 36-43.

Current Opinion in Cell Biology, 5(2) (April 1993) contains a number of brief reviews on aspects of cell signalling. Those by Beverly Errede and Daniel Levine (pp. 254-60) and by Alan Hall (pp. 265-8) are the most relevant.

Gene knock-outs/gene maps/gene add-ons to plants

A special supplement in *Science* 256: 766-813 (8 May 1992) consists of a number of reviews on gene knock-outs, gene add-ons and gene therapy.

Charles S. Gasser and Robert T. Fraley write on genetic crops in *Scientific American*, June 1992: 34-9.

Antigen processing

Two good reviews appear in *Current Opinion in Immunology*, 5(1) (February 1993). They are by Jacques Neefjes and Frank Momburg (pp. 27-34) and by Hans-Georg Rammensee, Kirsten Falk and Olaf Rotzschke (pp. 35-44).

APPENDIX: STATISTICAL TABLES

EXPLANATORY NOTE

Notes concerning certain data are indicated by a footnote indicator † shown against the names of the relevant country or territory. The corresponding texts can be found at the end of the relevant table.

There are also general notes for each table preceding the country notes.

The following symbols are also used throughout the tables:

—	magnitude nil
0 or 0.0	magnitude less than half of unit employed
ooo	data not available
□	category not applicable
*	provisional or estimated data
./.	data included elsewhere in another category
→	the figure to the immediate left includes the data for the column(s) in which this symbol appears

STATISTICS ON SCIENCE AND TECHNOLOGY

This Appendix presents a selection of data on science and technology taken from UNESCO's *Statistical Yearbook 1992*, and as such is the result of the worldwide data collection effort by the Organization in the field of science and technology. Most of the data were obtained from replies to the annual statistical questionnaires on manpower and expenditure for research and experimental development (R&D) sent to the Member States of UNESCO during recent years, completed or supplemented by data collected in the earlier surveys and from official reports and publications.

DEFINITIONS

The terms used in this Appendix may be defined as follows:

Type of personnel

Scientists and engineers: persons working in those capacities, i.e. as persons with scientific or technological training (usually completion of third-level education) in any field of science as defined below, who are engaged in professional work on R&D activities, administrators and other high-level personnel who direct the execution of R&D activities.

Technicians: persons engaged in that capacity in R&D activities who have received vocational or technical training in any branch of knowledge or technology of a specified standard (usually at least three years after the first stage of second-level education).

Auxiliary personnel: those whose work is directly associated with the performance of R&D activities, i.e. clerical, secretarial and administrative personnel, skilled, semi-skilled and unskilled workers in the various trades and all other auxiliary personnel. Excludes security, janitorial and maintenance personnel engaged in general housekeeping activities.

It should be noted that in general all personnel are considered for inclusion in the appropriate categories regardless of citizenship status or country of origin.

Scientific and technical manpower

An indication of the total numerical strength of qualified human resources is obtained either from the total stock or the number of economically active persons who possess the necessary qualifications to be scientists, engineers or technicians.

Total stock of qualified manpower (ST): The number of persons as described above, regardless of economic activity, age, sex, nationality or other characteristics, present in the domestic territory of a country at a given reference date.

Amount of economically active qualified manpower (EA): This group includes all persons of either sex, as specified above, who are engaged in, or actively seeking work in, any branch of the economy at a given reference date.

Full- and part-time R&D personnel and full-time equivalent

Data concerning personnel, especially scientists and engineers, are normally calculated in *full-time equivalent (FTE)*, which is a measurement unit representing one person working full-time for a given period; this unit is used to convert figures relating to the number of part-time workers into the equivalent number of full-time workers.

Research and experimental development (R&D)

In general R&D is defined as any creative systematic activity undertaken in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this knowledge to devise new applications. It includes fundamental research (i.e. experimental or theoretical work undertaken with no immediate practical purpose in mind), applied research in such fields as agriculture, medicine, industrial chemistry, etc. (i.e. research directed primarily towards a special practical aim or objective), and experimental development work leading to new devices, products or processes.

Field of study

The broad fields of S&T study used in these tables are the following:
Natural sciences, engineering and technology, medical sciences, agricultural sciences, social sciences and humanities, and other fields.

R&D expenditure

Total domestic expenditure on R&D activities refers to all expenditure made for this purpose in the course of a reference year in institutions and installations established in the national territory, as well as installations physically situated abroad.

The total expenditure for R&D comprises *current expenditure*, including overheads, and *capital expenditure.* Current intramural expenditure is further separated into labour costs and other current costs.

Source of funds

The following sources of finance for domestic expenditure on R&D activities are identified:

Government funds: include funds provided by the central (federal), state or local authorities.

Productive enterprise funds and special funds: funds allocated to R&D activities by institutions classified in the productive sector, and all sums received from the 'Technical and Economic Progress Fund' and other similar funds.

Foreign funds: funds received from abroad for national R&D activities.

Other funds: funds that cannot be classified under any of the preceding headings.

THE TABLES

In Table 1 data for scientists and engineers engaged in R&D are presented, distributed by field of study, i.e. the field of science of their qualification, and according to whether they are occupied full-time or part-time. Their full-time equivalent is also shown and where possible separate data are given for women.

Table 2 is concerned with recent trends in total personnel and the three types of personnel – scientists and engineers, technicians and auxiliary personnel – engaged in R&D.

Table 3 is devoted to scientific and technical manpower. It shows both the S&T manpower potential, i.e. those who possess the necessary qualifications to become scientists, engineers or technicians, and the scientists, engineers and technicians engaged in R&D related to the total population; the relationship between potential scientists and engineers and those engaged in R&D is also provided, as is the support ratio for scientists and engineers, i.e. the number of technicians per scientist or engineer engaged in R&D.

The structure of the financing of R&D can be seen in Table 4, which gives the distribution of total expenditure (or alternatively current expenditure) by four main categories of funding source. Again, the data are presented in national currencies and in percentages where the information is considered sufficiently complete to enable the reader to compare amongst countries the efforts of different financial supporters of R&D activities.

In Table 5 the absolute figures and the percentage distribution of current expenditure according to type of R&D activity – fundamental research, applied research or experimental development – are presented, thus showing the relative importance in terms of financial resources devoted to each of the types of such activity.

Table 6 presents data on total and current expenditure devoted to R&D activities. The relationship between current and total expenditure is also shown in percentage form, thus indicating any variations in the structure of R&D expenditure.

The indicators presented in Table 7 are concerned with the financial resources for R&D, showing expenditure for R&D related to the total population and to the number of scientists and engineers engaged in R&D, and also given as a percentage of gross national product (GNP).

Table 8 presents currency exchange rates for selected recent years and allows the financial data expressed in national currencies in Tables 4, 5, 6 and 7 to be used in a comparative way.

Readers seeking further statistics on science and technology are recommended to consult the *Statistical Yearbook*, published annually by UNESCO. Research workers interested in obtaining further details or clarification pertaining to particular countries as regards national definitions, coverage or limitations of the data presented in the Appendix tables may address their enquiries to the Division of Statistics, UNESCO, 7 place de Fontenoy, 75352 Paris 07-SP.

TABLE 1
NUMBER OF SCIENTISTS AND ENGINEERS ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT BY FIELD OF STUDY

COUNTRY/ TERRITORY	YEAR	SEX	TYPE OF DATA	TOTAL	FIELD OF STUDY					
					NATURAL SCIENCES	ENGINEERING AND TECHNOLOGY	MEDICAL SCIENCES	AGRICULTURAL SCIENCES	SOCIAL SCIENCES AND HUMANITIES	OTHER FIELDS
AFRICA										
BURUNDI†	1989	MF	FT+PT	170	49	15	3	75	22	6
CONGO†	1984	MF	FT+PT	862	145	68	50	285	245	69
EGYPT†	1982	MF	FT	9 950	1 605	2 605	2 050	3 143	547	—
		MF	PT	29 967	8 152	3 735	6 390	2 782	8 908	—
		MF	FTE	19 939	4 322	3 850	4 180	4 070	3 517	—
		F	FT+PT	11 503	3 075	1 189	3 109	1 186	2 944	—
LIBYAN ARAB JAMAHIRIYA	1980	MF	FTE	1 100	230	198	130	221	321	—
MAURITIUS	1989	MF	FT	178	9	38	8	99	24	—
		MF	PT	43	10	14	7	2	10	—
		MF	FTE	193	12	43	11	100	27	—
		F	FTE	33	—	6	4	17	6	—
SEYCHELLES†	1981	MF	FT	2	2	—	—	—	—	—
		MF	PT	—	—	—	—	—	—	—
		MF	FTE	2	2	—	—	—	—	—
		F	FTE	—	—	—	—	—	—	—
AMERICA, NORTH										
COSTA RICA	1988	MF	FT+PT	1 528	451	110	250	378	339	—
GUATEMALA†	1988	MF	FTE	858	103	111	189	249	206	—
MEXICO	1984	MF	FTE	16 679	3 786	2 690	3 866	2 385	3 952	—
		F	FTE	4 319	980	697	1 001	618	1 023	—
NICARAGUA	1987	MF	FT+PT	725	200	87	78	228	132	—
AMERICA, SOUTH										
ARGENTINA	1988	MF	FT	7 019	3 003	1 143	937	838	1 014	82
		MF	PT	16 369	5 292	2 195	2 078	2 401	4 034	371
		MF	FTE	11 088	4 543	1 689	1 407	1 487	1 793	169
		F	FTE	4 798	1 796	411	666	457	1 339	129
BRAZIL†	1985	MF	FTE	52 863	11 768	7 765	6 107	7 607	11 007	8 609
CHILE	1984	MF	FT	466	123	218	31	66	24	4
		MF	PT	3 844	988	838	1 061	155	758	44
		MF	FTE	1 587	485	474	284	110	220	14
COLOMBIA†	1982	MF	FT	831	288	49	21	334	139	—
		MF	PT	3 938	1 238	544	1 088	358	710	—
		MF	FTE	1 083	341	150	299	98	195	—
GUYANA†	1982	MF	FT	ooo	43	22	ooo	21	3	—
		MF	PT	—	—	—	—	—	—	—
		MF	FTE	ooo	43	22	ooo	21	3	—
URUGUAY	1987	MF	FT	752	90	132	189	172	126	43
		MF	PT	1 341	161	234	336	307	225	78
		MF	FT+PT	2 093	251	366	525	479	351	121
		F	FT+PT	720	86	126	181	165	121	41
VENEZUELA†	1983	MF	FT+PT	4 568	1 457	727	558	874	802	150
		MF	FTE	2 175	786	300	204	437	388	60
		F	FT+PT	1 479	438	134	302	171	375	59
ASIA										
INDIA†	1988	MF	FTE	*119 027	20 599	32 068	1 494	16 306	1 212	*47 348
		F	FTE	5 552	1 832	1 526	247	1 089	199	659
INDONESIA	1983	MF	FT+PT	18 533	5 317	3 285	1 615	4 083	4 233	—
ISRAEL	1984	MF	FT	14 173	5 900	5 000	500	500	2 200	—
		MF	PT	25 576	4 300	7 300	4 300	1 200	8 500	—
		MF	FTE	20 100	6 900	6 900	1 200	400	4 300	—
		F	FT+PT	10 400	3 300	800	1 300	300	4 600	—
JAPAN†	1981	MF	FT	379 405	80 442	142 316	64 408	26 598	41 316	24 325
		F	FT	22 475	2 277	775	7 850	904	4 108	6 561
JORDAN†	1982	MF	FT+PT	1 241	310	340	118	92	381	—

TABLE 1 cont.
NUMBER OF SCIENTISTS AND ENGINEERS ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT BY FIELD OF STUDY

COUNTRY/ TERRITORY	YEAR	SEX	TYPE OF DATA	TOTAL	FIELD OF STUDY: NATURAL SCIENCES	ENGINEERING AND TECHNOLOGY	MEDICAL SCIENCES	AGRICULTURAL SCIENCES	SOCIAL SCIENCES AND HUMANITIES	OTHER FIELDS
ASIA cont.										
KOREA, REP. OF†	1983	MF	FT	30 309	4 706	16 371	3 964	3 589	—	1 679
		MF	PT	1 808	171	1 373	101	130	—	33
PAKISTAN†	1982	MF	FT	ooo	—	929	821	2 149	—	606
		MF	PT	ooo	1 211	730	—	729	—	—
		MF	FTE	5 397	406	1 172	821	2 392	—	606
		F	FTE	418	152	114	80	56	—	16
PHILIPPINES	1984	MF	FT+PT	4 830	576	1 419	421	1 272	1 011	131
		F	FT+PT	2 319	322	480	344	471	630	72
QATAR†	1986	MF	FT+PT	229	160	53	2	5	—	9
		F	FT+PT	58	57	—	1	—	—	—
SINGAPORE†	1987	MF	FT+PT	3 361	863	2 007	436	55	—	—
SRI LANKA	1985	MF	FT	2 526	1 503	229	195	—	599	—
		MF	PT	794	169	191	40	—	394	—
		MF	FTE	2 790	1 560	293	208	—	729	—
		F	FTE	667	416	27	74	—	150	—
THAILAND	1987	MF	FT+PT	8 498	1 669	1 176	1 570	1 849	2 229	—
TURKEY†	1983	MF	FTE	7 309	891	1 040	1 350	1 590	531	1 907
EUROPE										
AUSTRIA†	1985	MF	FTE	4 591	1 500	739	590	282	1 480	—
BULGARIA	1987	MF	FTE	50 585	5 162	11 861	4 653	2 551	5 919	20 439
		F	FTE	22 268	2 185	3 463	2 163	720	2 906	10 831
FINLAND	1983	MF	FTE	10 951	2 291	5 211	890	572	1 947	40
GERMANY†										
FORMER GDR†	1989	MF	FTE	127 449	15 480	88 542	9 232	8 376	5 819	→
HUNGARY†	1987	MF	FT+PT	38 232	3 983	18 155	3 735	2 935	9 130	294
		F	FT+PT	11 122	1 207	3 498	1 426	779	4 055	157
MALTA†	1987	MF	FTE	34	3	7	10	—	14	—
NORWAY	1985	MF	FTE	9 692	1 833	4 421	945	456	1 797	240
POLAND†	1989	MF	FT	15 700	3 700	6 500	1 700	1 300	2 300	200
		MF	PT	50 600	13 900	13 500	8 800	5 300	7 500	1 600
		MF	FTE	32 500	8 300	11 000	4 600	3 100	4 800	700
PORTUGAL†	1980	MF	FT	1 790	529	246	123	307	300	285
		MF	PT	2 023	561	410	304	162	293	293
		MF	FTE	2 663	808	416	251	383	430	375
FORMER YUGOSLAVIA†	1980	MF	FT+PT	27 135	4 988	8 357	2 982	3 098	5 014	2 696
OCEANIA										
AUSTRALIA†	1986	MF	FTE	33 768	7 625	4 498	3 049	3 720	6 683	8 193
FRENCH POLYNESIA†	1983	MF	FT	17	8	1	7	—	1	—
		MF	PT	—	—	—	—	—	—	—
		MF	FTE	17	8	1	7	—	1	—
NEW CALEDONIA†	1985	MF	FT	77	48	8	3	14	3	1
		MF	PT	2	—	2	—	—	—	—
		MF	FTE	77	48	8	3	14	3	1
TONGA†	1981	MF	FT	9	—	—	—	9	—	—
		MF	PT	2	—	—	—	2	—	—

TABLE 1

GENERAL NOTES

FT = FULL-TIME

PT = PART-TIME

FT+PT = FULL-TIME PLUS PART-TIME

FTE = FULL-TIME EQUIVALENT

— MAGNITUDE NIL

* PROVISIONAL OR ESTIMATED DATA

ooo DATA NOT AVAILABLE

→ THE FIGURE TO THE IMMEDIATE LEFT INCLUDES THE DATA FOR THE COLUMN IN WHICH THIS SYMBOL APPEARS

† COUNTRY NOTES

AFRICA

Burundi: Not including data for the productive sector.
Congo: Not including military and defence R&D.
Egypt: Not including military and defence R&D.
Seychelles: Not including military and defence R&D.

AMERICA, NORTH

Guatemala: Not including data for the productive sector (non-integrated R&D).

AMERICA, SOUTH

Brazil: Not including data either for scientists and engineers engaged in private productive enterprises or for military and defence R&D.
Colombia: Not including data for the productive sector (non-integrated R&D).
Guyana: Not including military and defence R&D. Data for the general service sector and for medical sciences in the higher education sector are also excluded.
Venezuela: Not including military and defence R&D.

ASIA

India: The total number of scientists and engineers in final column includes 22 100 (estimate for 1982) personnel in the higher education sector.
Japan: Data relate to regular research workers only Not including social sciences and humanities in the productive sector (integrated R&D).
Jordan: Not including military and defence R&D.
Korea, Republic of: Not including military and defence R&D nor social sciences and humanities.
Pakistan: Data relate to R&D activities concentrated mainly in government-financed research establishments only; social sciences and humanities in the higher education and general service sectors are excluded. Not including military and defence R&D.
Qatar: Not including social sciences and humanities in the higher education sector.
Singapore: Not including R&D in social sciences and humanities.
Turkey: Not including data for the productive sector Social sciences and humanities in the general service sector are also excluded.

EUROPE

Austria: Not including data for the productive sector (integrated R&D).
Germany:
Former German Democratic Republic: Data in social sciences and humanities column refer only to economics and computer sciences.
Hungary: Not including scientists and engineers in the administration of R&D. Of military R&D, only that part carried out in civil establishments is included.
Malta: Data relate to the higher education sector only.
Poland: Not including data for the productive sector (integrated R&D) nor military and defence R&D.
Portugal: Data in final column refer to scientists and engineers engaged in the productive sector (integrated R&D) for whom a distribution by field of study is unknown.
Former Yugoslavia: Not including military and defence R&D.

OCEANIA

Australia: Data in final column refer to scientists and engineers engaged in the productive sector (integrated R&D) for whom a distribution by field of study is unknown.
French Polynesia: Data relate to one research institute only.
New Caledonia: Data refer only to six out of 11 research institutes.
Tonga: Data relate to one research institute only.

TABLE 2
PERSONNEL ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

COUNTRY/ TERRITORY	YEAR	PERSONNEL ENGAGED IN R&D TOTAL (FTE)	SCIENTISTS AND ENGINEERS	TECHNICIANS	AUXILIARY PERSONNEL
AFRICA					
BURUNDI†#	1984	515	114	90	311
	1989	814	170	168	476
COTE D'IVOIRE†	1973	∞∞	368	∞∞	∞∞
	1974	877	463	92	322
	1975	∞∞	502	∞∞	∞∞
EGYPT†	1978	∞∞	18 350	5 254	∞∞
	1982	46 796	19 939	6 678	20 179
	1986	51 183	20 893	7 532	22 758
GABON†#	1985	∞∞	188	∞∞	∞∞
	1986	∞∞	211	∞∞	∞∞
	1987	∞∞	199	∞∞	∞∞
GHANA	1974	8 906	3 704	5 202	→
	1975	9 351	3 889	5 462	→
	1976	9 819	4 084	5 735	→
MADAGASCAR†#	1987	1 673	205	688	780
	1988	1 714	228	724	762
	1989	1 837	269	956	612
MAURITIUS	1980	1 069	152	108	809
	1985	1 113	267	191	655
	1989	1 021	193	172	656
NIGER†	1974	∞∞	53	∞∞	∞∞
	1975	∞∞	79	∞∞	∞∞
	1976	94	93	1	—
NIGERIA†	1985	13 924	1 422	6 565	5 937
	1986	12 845	1 499	6 005	5 341
	1987	12 880	1 138	6 042	5 500
RWANDA	1983	149	64	55	30
	1984	164	69	60	35
	1985	*183	71	*67	*45
SENEGAL#	1971	∞∞	416	∞∞	∞∞
	1972	∞∞	609	516	∞∞
	1976	∞∞	522	∞∞	∞∞
SEYCHELLES†	1980	3	2	1	—
	1981	3	2	1	—
	1983	33	18	6	9
SUDAN#	1971	6 378	1 299	222	4 857
	1974	16 598	3 324	1 798	11 476
	1978	22 675	4 345	3 271	15 059
ZAMBIA	1970	∞∞	*75	*210	∞∞
	1973	1 060	260	800	→
AMERICA, NORTH					
CANADA†	1980	63 190	29 320	17 460	16 410
	1985	76 985	37 853	21 497	17 635
	1988	109 330	61 130	27 080	21 120
CUBA†	1980	21 521	5 637	6 556	9 328
	1985	34 150	10 305	9 238	14 607
	1989	32 614	12 052	8 830	11 732

TABLE 2 cont.
PERSONNEL ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

COUNTRY/ TERRITORY	YEAR	PERSONNEL ENGAGED IN R&D: TOTAL (FTE)	SCIENTISTS AND ENGINEERS	TECHNICIANS	AUXILIARY PERSONNEL
AMERICA, NORTH cont.					
EL SALVADOR†#	1980	ooo	533	1 547	ooo
	1981	ooo	564	1 971	ooo
GUATEMALA	1970	ooo	*230	*134	ooo
	1972	ooo	*267	*255	ooo
	1974	ooo	310	439	ooo
JAMAICA†	1984	100	23	21	56
	1985	121	21	31	69
	1986	104	18	15	71
MEXICO†	1971	*13 525	*4 064	*7 181	*2 280
	1974	ooo	8 446	ooo	ooo
	1984	68 972	16 679	29 467	22 826
NICARAGUA#	1985	1 803	650	212	941
	1987	2 005	725	302	978
ST LUCIA	1982	ooo	40	103	ooo
	1983	ooo	46	81	ooo
	1984	ooo	53	86	ooo
TRINIDAD AND TOBAGO	1982	588	174	182	232
	1983	625	187	205	233
	1984	806	275	254	277
TURKS AND CAICOS ISLANDS	1975	3	3	—	—
	1976	2	2	—	—
	1984	—	—	—	—
UNITED STATES†	1980	ooo	658 700	ooo	ooo
	1985	ooo	849 200	ooo	ooo
	1988	ooo	*949 200	ooo	ooo
AMERICA, SOUTH					
ARGENTINA	1980	ooo	*9 500	*13 300	ooo
	1985	*28 900	*10 800	*7 100	*11 000
	1988	22 855	11 088	6 241	5 526
BRAZIL†#	1983	ooo	38 713	ooo	ooo
	1984	ooo	47 870	ooo	ooo
	1985	ooo	52 863	ooo	ooo
CHILE†#	1981	ooo	3 469	ooo	ooo
	1985	ooo	4 907	ooo	ooo
	1988	ooo	5 323	ooo	ooo
ECUADOR	1970	ooo	595	508	ooo
	1973	ooo	544	217	ooo
GUYANA†	1980	720	94	250	376
	1982	623	89	178	356
PERU†#	1970	ooo	1 925	ooo	ooo
	1975	ooo	3 750	ooo	ooo
	1980	ooo	9 171	5 218	ooo
VENEZUELA†#	1973	5 198	2 809	783	1 606
	1980	ooo	3 673	ooo	ooo
	1983	10 687	4 568	2 692	3 427

TABLE 2 *cont.*
PERSONNEL ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

		PERSONNEL ENGAGED IN R&D			
COUNTRY/ TERRITORY	YEAR	TOTAL (FTE)	SCIENTISTS AND ENGINEERS	TECHNICIANS	AUXILIARY PERSONNEL
ASIA					
BRUNEI	1982	104	23	81	—
DARUSSALAM†#	1983	188	21	70	97
	1984	243	20	116	107
CYPRUS†	1982	125	47	78	→
	1983	129	49	80	→
	1984	131	51	80	→
INDIA†	1984	*244 049	*100 136	72 233	71 680
	1986	*262 797	*107 409	70 233	79 093
	1988	*289 716	*119 027	80 956	86 398
INDONESIA#	1985	ooo	21 160	3 888	ooo
	1987	ooo	30 486	ooo	ooo
	1988	ooo	32 038	ooo	ooo
IRAN, ISLAMIC	1970	6 432	3 007	482	2 943
REPUBLIC OF	1972	9 865	4 896	857	4 112
	1985	ooo	3 194	1 854	ooo
IRAQ†	1972	248	170	78	→
	1973	316	205	111	→
	1974	365	240	125	→
ISRAEL†	1974	ooo	12 200	ooo	ooo
	1978	ooo	14 722	ooo	ooo
	1984	ooo	14 173	ooo	ooo
JAPAN†	1980	601 192	441 186	86 970	73 036
	1985	730 432	548 249	99 280	82 903
	1989	830 855	636 817	105 430	88 608
JORDAN†	1975	ooo	235	213	ooo
	1985	ooo	400	29	ooo
	1989	463	422	41	ooo
KOREA,	1980	30 473	18 434	7 417	4 622
REPUBLIC OF†#	1985	73 516	41 473	24 152	7 891
	1988	104 737	56 545	35 720	12 472
KUWAIT†#	1982	1 864	1 013	443	408
	1983	2 064	1 157	470	437
	1984	2 539	1 511	561	467
LEBANON†	1978	160	160	—	—
	1979	175	170	5	→
	1980	206	180	6	20
PAKISTAN†	1981	22 922	5 144	6 476	11 302
	1982	24 723	5 397	7 138	12 188
	1988	28 990	6 641	9 286	13 063
PHILIPPINES#	1982	17 992	7 884	3 500	6 608
	1983	9 949	4 394	1 867	3 688
	1984	10 185	4 830	1 855	3 500
SINGAPORE†#	1981	2 741	1 193	807	741
	1984	4 886	2 401	1 359	1 126
	1987	5 876	3 361	1 526	989

TABLE 2 cont.
PERSONNEL ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

		PERSONNEL ENGAGED IN R&D			
COUNTRY/ TERRITORY	YEAR	TOTAL (FTE)	SCIENTISTS AND ENGINEERS	TECHNICIANS	AUXILIARY PERSONNEL
ASIA cont.					
SRI LANKA	1983	ooo	1 939	*480	ooo
	1984	ooo	2 619	592	ooo
	1985	ooo	2 790	693	ooo
TURKEY	1984	27 007	9 914	6 284	10 809
	1985	29 241	11 276	7 367	10 598
VIET NAM†	1976	24 560	11 230	13 330	→
	1978	25 050	13 050	6 040	5 960
	1985	ooo	20 000	ooo	ooo
EUROPE					
AUSTRIA	1975	15 392	5 387	4 944	5 061
	1981	18 599	6 712	6 145	5 742
	1984	20 161	7 609	6 817	5 735
BELGIUM	1975	30 131	13 883	6 570	9 677
	1986	36 203	15 705	20 498	→
	1988	36 770	16 646	20 124	→
BULGARIA†	1980	72 335	38 706	10 483	23 146
	1985	90 308	48 008	13 099	29 201
	1987	96 471	50 585	11 662	34 224
CZECHOSLOVAKIA†	1980	171 789	53 659	60 552	57 578
	1985	180 439	61 046	47 337	72 056
	1989	185 492	65 475	42 876	77 141
DENMARK	1981	16 476	6 785	9 691	→
	1985	19 914	8 567	11 347	→
	1989	25 448	10 662	14 786	→
FINLAND	1981	18 004	9 722	8 282	→
	1985	*23 551	ooo	ooo	ooo
	1989	*28 925	ooo	ooo	ooo
FRANCE	1980	236 200	74 900	161 300	→
	1985	273 000	102 300	170 700	→
	1988	283 099	115 163	167 936	→
GERMANY†					
FORMER GDR†	1980	191 429	120 473	70 956	→
	1985	191 262	122 292	68 970	→
	1989	195 073	127 449	67 624	→
FEDERAL REPUBLIC OF GERMANY†	1981	359 419	124 678	103 214	131 527
	1985	398 328	143 627	118 080	136 621
	1987	419 206	165 614	122 458	131 133
GREECE†	1979	4 308	2 634	984	690
	1983	4 873	2 441	1 067	1 365
HUNGARY†	1980	62 866	25 589	23 707	13 570
	1985	48 745	22 479	17 869	8 397
	1989	42 276	20 431	14 113	7 732
ICELAND	1981	744	398	346	→
	1985	818	512	306	→
	1989	1 177	773	404	→

TABLE 2 cont.
PERSONNEL ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

COUNTRY/ TERRITORY	YEAR	PERSONNEL ENGAGED IN R&D			
		TOTAL (FTE)	SCIENTISTS AND ENGINEERS	TECHNICIANS	AUXILIARY PERSONNEL
EUROPE cont.					
IRELAND	1981	5 474	2 635	1 408	1 431
	1985	6 264	3 741	1 340	1 183
	1988	8 590	6 351	1 291	948
ITALY	1980	95 803	46 999	27 605	21 199
	1985	117 887	63 759	33 058	21 070
	1988	135 665	74 833	38 287	22 545
MALTA†	1983	46	34	5	7
	1985	46	34	5	7
	1988	46	34	5	7
NETHERLANDS†	1980	53 560	26 430	27 130	→
	1985	61 400	33 620	27 780	→
	1988	64 420	37 520	26 900	→
NORWAY†	1980	15 005	7 427	7 578	→
	1985	18 781	9 692	9 089	→
	1989	*20 700	*12 100	*8 600	→
POLAND†	1980	240 000	93 000	57 000	90 000
	1985	181 000	57 000	54 000	70 000
	1989	ooo	32 500	ooo	ooo
PORTUGAL	1980	7 711	2 663	2 867	2 181
	1984	9 267	3 475	3 059	2 733
	1988	10 883	5 004	3 571	2 308
ROMANIA	1987	167 049	58 647	42 195	66 207
	1988	167 711	58 879	42 362	66 470
	1989	169 964	59 670	42 931	67 363
SPAIN†	1980	30 905	13 732	4 710	12 463
	1985	40 653	21 455	7 024	12 174
	1988	54 337	31 170	9 914	13 253
SWEDEN†	1981	42 214	17 696	24 518	→
	1985	49 599	21 899	27 700	→
	1987	51 811	22 725	29 086	→
SWITZERLAND	1977	*36 920	*16 000	*20 920	→
	1979	37 945	16 410	15 840	5 695
	1986	45 200	14 910	10 710	19 580
UNITED KINGDOM†	1972	258 746	77 086	80 220	101 440
	1975	259 100	79 300	75 800	104 000
	1978	261 400	86 500	76 600	98 300
FORMER YUGOSLAVIA†	1980	53 699	22 951	13 431	17 317
	1985	68 591	30 564	16 363	21 664
	1989	78 704	34 770	18 780	25 154
OCEANIA					
AMERICAN SAMOA†	1970	14	2	12	→
	1971	15	3	2	10
AUSTRALIA	1981	45 211	24 486	12 284	8 441
	1985	53 258	30 406	14 848	8 544
	1988	64 820	38 568	16 535	9 717

TABLE 2 cont.
PERSONNEL ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

		PERSONNEL ENGAGED IN R&D			
COUNTRY/ TERRITORY	YEAR	TOTAL (FTE)	SCIENTISTS AND ENGINEERS	TECHNICIANS	AUXILIARY PERSONNEL
OCEANIA cont.					
FIJI†#	1984	140	28	82	30
	1985	146	30	86	30
	1986	156	36	90	30
FRENCH POLYNESIA†	1980	101	19	13	69
	1982	101	21	14	66
	1983	97	17	16	64
GUAM†	1979	52	21	19	12
	1985	*46	19	*11	*16
	1989	*52	*21	*11	*20
KIRIBATI	1980	3	2	1	—
	1981	3	2	1	—
NEW CALEDONIA†	1983	17	7	5	5
	1984	82	12	33	37
	1985	334	77	71	186
NEW ZEALAND†	1973	ooo	*2 950	ooo	ooo
	1975	8 003	3 659	3 164	1 180
	1979	8 080	ooo	ooo	ooo
PACIFIC ISLANDS	1973	66	23	24	19
	1978	22	5	11	6
	1979	23	4	11	8
PAPUA NEW GUINEA	1971	ooo	*110	ooo	ooo
	1972	ooo	*115	ooo	ooo
	1973	ooo	131	ooo	ooo
SAMOA†	1976	254	135	82	37
	1977	266	140	87	39
	1978	280	140	92	48
TONGA†#	1979	ooo	9	1	ooo
	1980	ooo	10	4	ooo
	1981	ooo	11	4	ooo
VANUATU	1973	29	2	1	26
	1974	39	4	1	34
	1975	39	3	1	35
FORMER USSR					
FORMER USSR†	1980	ooo	1 373 300	ooo	ooo
	1985	ooo	1 491 300	ooo	ooo
	1990	ooo	1 694 400	ooo	ooo
BELARUS†	1980	ooo	38 130	ooo	ooo
	1985	ooo	42 500	ooo	ooo
	1988	ooo	44 100	ooo	ooo
UKRAINE†	1980	ooo	195 782	ooo	ooo
	1985	ooo	210 300	ooo	ooo
	1989	ooo	348 600	ooo	ooo

TABLE 2

GENERAL NOTES

DATA ARE EXPRESSED IN FULL-TIME EQUIVALENT (FTE) EXCEPT FOR COUNTRIES WITH THE SYMBOL #

# INDICATES THE NUMBER OF FULL-TIME PLUS PART-TIME R&D PERSONNEL

— MAGNITUDE NIL

ooo DATA NOT AVAILABLE

* PROVISIONAL OR ESTIMATED DATA

→ THE FIGURE TO THE IMMEDIATE LEFT INCLUDES THE DATA FOR THE COLUMN(S) IN WHICH THIS SYMBOL APPEARS

† COUNTRY NOTES

AFRICA

Burundi: Not including data for the productive sector.
Côte d'Ivoire: Data for scientists and engineers refer only to full-time.
Egypt: Not including military and defence R&D.
Gabon: Not including data for the productive sector.
Madagascar: Not including data for the higher education sector.
Niger: Data relate to the higher education sector only.
Nigeria: Data relate only to 23 out of 26 national research institutes under the Federal Ministry of Science and Technology.
Seychelles: Not including military and defence R&D.

AMERICA, NORTH

Canada: Due to methodological changes, data from 1986 are not comparable with the previous years. Not including social sciences and humanities in the productive sector (integrated R&D).
Cuba: Not including military and defence R&D.
El Salvador: Data refer to scientists and engineers and technicians engaged in public enterprises.
Jamaica: Data relate to the Scientific Research Council only.
Mexico: Data for 1971 and 1974 refer to full-time plus part-time personnel.
United States: Not including data for law, humanities and education.

AMERICA, SOUTH

Brazil: Not including military and defence R&D. Not including scientists and engineers engaged in private productive enterprises.
Chile: Not including military and defence R&D.
Guyana: Not including military and defence R&D. Data for the general service sector and for medical sciences in the higher education sector are also excluded.
Peru: Data also include scientific and technological services (STS).
Venezuela: Not including military and defence R&D.

ASIA

Brunei Darussalam: Data refer to two research institutes only
Cyprus: Not including data for the productive sector.
India: Data relating to technicians and auxiliary personnel in the higher education sector are not included. The number of scientists and engineers in the higher education sector in 1984, 1986 and 1988 is 22 100 (1982 estimate). In 1986 and 1988, the total column includes respectively 6 062 and 3 335 persons for whom the category of personnel is unknown.
Iraq: Data relate to the Foundation of Scientific Research only. In 1974 there were 1 862 persons (of whom 1 486 scientists and engineers) working in government departments concerned with scientific activities.
Israel: Data refer to full-time scientists and engineers in the civilian sector only and do not include social sciences and humanities.
Japan: Data refer to full-time personnel. Not including data for social sciences and humanities in the productive sector (integrated R&D)
Jordan: Not including military and defence R&D.
Korea, Republic of: Not including military and defence R&D nor social sciences and humanities.
Kuwait: Data refer to scientific and technological activities (STA).
Lebanon: Partial data referring to the Faculty of Science at the University of Lebanon only.
Pakistan: Not including military and defence R&D. Data relate to R&D activities concentrated mainly in government-financed research establishments; social sciences and humanities in the higher education and general service sectors are excluded.
Singapore: Not including social sciences and humanities.
Viet Nam: Data for 1976 and 1978 do not include technicians and auxiliary personnel in the higher education sector. In 1985 the general service sector is excluded.

EUROPE

Bulgaria: Data do not include technicians and auxiliary personnel in the higher education sector.
Czechoslovakia: Due to methodological changes, data since 1981 are not strictly comparable with the previous years. Scientists and engineers engaged in the administration of R&D are included with auxiliary personnel; of military R&D, only that part carried out in civil establishments is included.
Germany:
Former German Democratic Republic: In 1985 and 1989, with the exception of economics and computer sciences, R&D in social sciences and humanities is excluded
Federal Republic of Germany: Not including social sciences and humanities in the productive sector.
Greece: Data relate to government activities only.
Hungary: Due to methodological changes, data since 1981 are not comparable with the previous years. Not including personnel engaged in the administration of R&D. Skilled workers are counted with technicians rather than with auxiliary personnel. The latter also include security, maintenance and repair personnel. Of military R&D, only that part carried out in civil establishments included.
Malta: Data relate to the higher education sector only.
Netherlands: Due to methodological changes, data since 1981 are not strictly comparable with the previous years Not including social sciences and humanities in the productive sector (integrated R&D).
Norway: Data for 1980 do not include private enterprises in the productive sector.
Poland: Due to methodological changes, data since 1985 are not comparable with previous years. Not including military and defence R&D. For 1985, data do not include technicians and auxiliary personnel in the higher education sector. For 1989, data relating to the productive sector (integrated R&D) are excluded.
Spain: Due to methodological changes, data since 1984 are not comparable with previous years. Not including private non-profit organizations. Data do not include technicians and auxiliary personnel in the higher education sector.
Sweden: Not including social sciences and humanities in the productive and general service sectors
United Kingdom: Not including data for the higher education sector.
Former Yugoslavia: Not including military and defence R&D.

OCEANIA

American Samoa: Data relate to one research institute only.
Fiji: Data relate to one research institute only.
French Polynesia: Data relate to full-time personnel in one research institute only.
Guam: Data relate to the higher education sector only.
New Caledonia: Data refer to the following number of research institutes in 1983: two; in 1984: three; and in 1985: six.
New Zealand: Data for 1975 do not include auxiliary personnel in the higher education sector.
Samoa: Data for scientists and engineers refer only to full-time
Tonga: Data relate to one research institute only.

FORMER USSR

Former USSR: Data refer to all persons with a higher scientific degree or scientific title, regardless of the nature of their work, persons undertaking research work in scientific establishments and scientific teaching staff in institutions of higher education; they also include persons undertaking scientific work in industrial enterprises.
Belarus: See note for the former USSR.
Ukraine: See note for the former USSR.

TABLE 3
SELECTED INDICATORS FOR SCIENTIFIC AND TECHNICAL MANPOWER AND PERSONNEL ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT

			QUALIFIED MANPOWER		PERSONNEL ENGAGED IN R&D			
COUNTRY/ TERRITORY	YEAR	TYPE OF DATA	POTENTIAL SCIENTISTS AND ENGINEERS PER MILLION POPULATION	POTENTIAL TECHNICIANS PER MILLION POPULATION	SCIENTISTS AND ENGINEERS PER MILLION POPULATION	TECHNICIANS PER MILLION POPULATION	NUMBER OF TECHNICIANS PER SCIENTIST OR ENGINEER	S&E IN R&D AS % OF POTENTIAL S&E
AFRICA								
BENIN	1989	EA	299	ooo	177	54	0.3	59.2
BURUNDI	1989	□	ooo	ooo	32	32	1.0	ooo
CENTRAL AFRICAN REPUBLIC	1984	□	ooo	ooo	76	149	2.0	ooo
CONGO	1984	□	ooo	ooo	458	783	1.7	ooo
EGYPT	1986	□	ooo	ooo	439	158	0.4	ooo
GABON	1987	□	ooo	ooo	192	17	0.1	ooo
GUINEA	1984	□	ooo	ooo	263	125	0.5	ooo
KENYA	1982	EA	906	989	ooo	ooo	ooo	ooo
LIBYAN ARAB JAMAHIRIYA	1980	EA	14 373	2 964	361	493	1.4	2.5
MADAGASCAR	1989	□	ooo	ooo	23	82	3.6	ooo
MAURITIUS†	1989	ST	7 662	10 825	180	160	0.9	2.3
NIGERIA†	1987	ST	281	1 014	14	61	4.5	5.0
RWANDA	1985	□	ooo	ooo	12	*11	*0.9	ooo
SENEGAL	1981	□	ooo	ooo	342	468	1.4	ooo
SEYCHELLES	1983	□	ooo	ooo	281	94	0.3	ooo
AMERICA, NORTH								
CANADA†	1988	EA	63 440	119 752	2 347	1 040	0.4	3.7
COSTA RICA†	1988	EA	21 029	ooo	534	ooo	ooo	2.5
CUBA†	1989	ST	14 233	ooo	1 146	839	0.7	8.0
EL SALVADOR	1989	□	ooo	ooo	27	316	11.5	ooo
GUATEMALA†	1990	□	2 967	ooo	99	106	1.1	3.3
HAITI	1982	EA	2 538	3 224	ooo	ooo	ooo	ooo
JAMAICA	1986	□	ooo	ooo	8	6	0.8	ooo
MEXICO	1984	□	ooo	ooo	215	379	1.8	ooo
NICARAGUA	1987	□	ooo	ooo	207	86	0.4	ooo
ST LUCIA	1984	□	ooo	ooo	396	642	1.6	ooo
TRINIDAD AND TOBAGO	1984	□	ooo	ooo	237	219	0.9	ooo
UNITED STATES	1988	EA	21 576	ooo	*3 874	ooo	ooo	*18.0
AMERICA, SOUTH								
ARGENTINA	1988	EA	22 044	7 771	*352	*198	*0.6	*1.6
BRAZIL†	1985	ST	11 231	ooo	390	ooo	ooo	3 5
CHILE	1988	□	ooo	ooo	363	231	0.6	ooo
COLOMBIA	1982	□	ooo	ooo	39	36	0.9	ooo
GUYANA†	1982	EA	1 990	443	115	230	2.0	5.8
PARAGUAY	1981	□	ooo	ooo	248	→	ooo	ooo
PERU	1981	ST	16 465	9 348	274	ooo	ooo	1.7
URUGUAY†	1987	ST	*19 166	ooo	686	ooo	ooo	3.6
VENEZUELA†	1983	EA	21 820	ooo	279	165	0.6	1.3
ASIA								
BAHRAIN	1981	ST	30 359	32 811	ooo	ooo	ooo	ooo

TABLE 3 cont.
SELECTED INDICATORS FOR SCIENTIFIC AND TECHNICAL MANPOWER AND PERSONNEL ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT

			QUALIFIED MANPOWER		PERSONNEL ENGAGED IN R&D			
COUNTRY/ TERRITORY	YEAR	TYPE OF DATA	POTENTIAL SCIENTISTS AND ENGINEERS PER MILLION POPULATION	POTENTIAL TECHNICIANS PER MILLION POPULATION	SCIENTISTS AND ENGINEERS PER MILLION POPULATION	TECHNICIANS PER MILLION POPULATION	NUMBER OF TECHNICIANS PER SCIENTIST OR ENGINEER	S&E IN R&D AS % OF POTENTIAL S&E
ASIA cont.								
BRUNEI DARUSSALAM†	1984	EA	11 531	22 401	93	540	5.8	0.9
CHINA	1988	EA	8 157	→	ooo	ooo	ooo	ooo
CYPRUS†	1987	EA	*34 200	*28 931	77	121	1.6	0.2
HONG KONG	1986	EA	32 617	21 487	ooo	ooo	ooo	ooo
INDIA†	1990	EA	2 897	749	*145	*99	*0.7	5.0
INDONESIA†	1988	ST	1 280	11 026	181	ooo	ooo	14.1
IRAN, ISLAMIC REPUBLIC OF†	1985	ST	6 992	4 056	67	39	0.6	1.0
ISRAEL	1984	EA	41 992	42 058	4 836	1 035	0.2	11.5
JAPAN†	1989	EA	71 223	40 695	5 183	858	0.2	7.8
JORDAN	1986	EA	8 564	ooo	119	8	0.1	1.4
KOREA, REP. OF†	1988	EA	*2 428	*49 790	1 343	849	0.6	55.3
KUWAIT†	1985	ST	35 115	41 269	925	344	0.4	2.6
LEBANON	1980	□	ooo	ooo	67	2	0.0	ooo
MALAYSIA†	1988	ST	1 792	ooo	327	69	0.2	18.2
NEPAL	1980	EA	247	*494	22	5	0.2	9.1
PAKISTAN†	1990	EA	2 340	1 713	58	81	1.4	2.5
PHILIPPINES†	1984	ST	36 649	ooo	90	35	0.4	0.2
QATAR†	1986	EA	23 781	13 208	746	199	0.3	3.1
SINGAPORE†	1987	EA	15 849	10 737	1 283	583	0.5	8.1
SRI LANKA	1985	EA	1 337	ooo	173	43	0.2	13.0
THAILAND	1987	□	ooo	ooo	104	52	0.5	ooo
TURKEY†	1985	ST	15 932	18 678	224	146	0.7	1.4
VIET NAM	1985	□	ooo	ooo	334	ooo	ooo	ooo
EUROPE								
AUSTRIA†	1984	EA	17 781	3 768	1 007	903	0.9	5.7
BELGIUM	1988	□	ooo	ooo	1 691	2 045	1.2	ooo
BULGARIA†	1987	EA	36 101	77 039	5 641	1 301	0.2	15.6
CZECHOSLOVAKIA†	1989	EA	35 443	ooo	4 195	2 747	0.7	11.8
DENMARK†	1989	ST	22 740	62 304	2 074	2 877	1.4	9.1
FINLAND†	1989	ST	55 416	49 315	2 283	1 993	0.9	4.1
FRANCE†	1988	□	ooo	ooo	2 071	3 020	1.5	ooo
GERMANY†								
FORMER GDR†	1989	EA	38 270	66 913	7 819	4 149	0.5	20.4
FEDERAL REPUBLIC OF GERMANY	1987	EA	45 571	32 466	2 713	2 006	0.7	6.0
GREECE†	1986	ST	33 905	16 049	54	49	0.9	0.2
HUNGARY†	1988	EA	45 786	→	1 936	1 337	0.7	4.2
ICELAND†	1989	□	ooo	ooo	3 080	1 610	0.5	4.3
IRELAND†	1988	EA	40 618	201 252	1 737	353	0.2	ooo
ITALY†	1988	EA	20 784	62 381	1 310	670	0.5	6.3
MALTA	1988	□	ooo	ooo	97	14	0.1	ooo
NETHERLANDS†	1988	EA	67 129	→	2 543	1 823	0.7	3.8
NORWAY†	1989	ST	28 915	ooo	*2 882	*2 048	*0.7	10.0
POLAND†	1988	EA	38 658	131 513	854	ooo	ooo	2.2

TABLE 3 cont.
SELECTED INDICATORS FOR SCIENTIFIC AND TECHNICAL MANPOWER AND PERSONNEL ENGAGED IN RESEARCH AND EXPERIMENTAL DEVELOPMENT

			QUALIFIED MANPOWER		PERSONNEL ENGAGED IN R&D			
COUNTRY/ TERRITORY	YEAR	TYPE OF DATA	POTENTIAL SCIENTISTS AND ENGINEERS PER MILLION POPULATION	POTENTIAL TECHNICIANS PER MILLION POPULATION	SCIENTISTS AND ENGINEERS PER MILLION POPULATION	TECHNICIANS PER MILLION POPULATION	NUMBER OF TECHNICIANS PER SCIENTIST OR ENGINEER	S&E IN R&D AS % OF POTENTIAL S&E
EUROPE cont.								
PORTUGAL	1988	□	ooo	ooo	488	348	0.7	ooo
ROMANIA	1989	□	ooo	ooo	2 582	1 858	0.7	ooo
SAN MARINO	1989	EA	22 783	80 565	—	—	—	—
SPAIN	1988	EA	39 602	→	799	254	0.3	2.0
SWEDEN†	1987	□	ooo	ooo	2 712	3 472	1.3	ooo
SWITZERLAND†	1986	EA	55 081	ooo	2 299	1 652	0.7	4.2
FORMER YUGOSLAVIA†	1989	EA	23 995	18 418	1 471	795	0.5	6.1
OCEANIA								
AUSTRALIA†	1988	EA	32 638	19 864	2 115	1 004	0.5	6.5
FIJI	1986	□	ooo	ooo	50	126	2.5	ooo
FRENCH POLYNESIA	1983	□	ooo	ooo	104	98	0.9	ooo
GUAM	1989	□	ooo	ooo	*179	94	*0.5	ooo
KIRIBATI	1980	□	ooo	ooo	34	17	0.5	ooo
NEW CALEDONIA	1985	□	ooo	ooo	507	467	0.9	ooo
TONGA	1981	□	ooo	ooo	113	41	0.4	ooo
FORMER USSR								
FORMER USSR†	1990	EA	55 275	71 756	5 871	ooo	ooo	10.6
BELARUS†	1988	EA	58 000	73 000	4 345	ooo	ooo	7.5
UKRAINE†	1989	EA	56 850	74 976	6 736	ooo	ooo	11.8

TABLE 3

GENERAL NOTES

DATA FOR PERSONNEL ENGAGED IN R&D ARE IN FULL-TIME EQUIVALENT

EA = ECONOMICALLY ACTIVE QUALIFIED MANPOWER

ST = STOCK OF QUALIFIED MANPOWER

S&E = SCIENTISTS AND ENGINEERS

— MAGNITUDE NIL

0 or 0.0 MAGNITUDE LESS THAN HALF OF UNIT EMPLOYED

ooo DATA NOT AVAILABLE

□ CATEGORY NOT APPLICABLE

* PROVISIONAL OR ESTIMATED DATA

→ THE FIGURE TO THE IMMEDIATE LEFT INCLUDES THE DATA FOR THE COLUMN(S) IN WHICH THIS SYMBOL APPEARS

† COUNTRY NOTES

AFRICA

Mauritius: Data for qualified manpower relate to 1983.
Nigeria: Data for qualified manpower relate to 1980.

AMERICA, NORTH

Canada: Data for qualified manpower relate to 1986.
Costa Rica: Data for qualified manpower relate to 1980.
Cuba: Data for qualified manpower relate to 1981.
Guatemala: Data for personnel engaged in R&D relate to 1988.

AMERICA, SOUTH

Brazil: Data for qualified manpower relate to 1980.
Guyana: Data for qualified manpower relate to 1980.
Uruguay: Data for qualified manpower relate to 1985.
Venezuela: Data for qualified manpower relate to 1982.

ASIA

Brunei Darussalam: Data for qualified manpower relate to 1981.
Cyprus: Data for personnel engaged in R&D relate to 1984. The number of technicians engaged in R&D includes auxiliary personnel.
India: Data for qualified manpower relate to 1988.
Indonesia: Data for qualified manpower relate to 1980.
Iran, Islamic Republic of: Data for qualified manpower relate to 1982.
Japan: Data for qualified manpower relate to 1987.
Korea, Republic of: Data for qualified manpower relate to 1981.
Kuwait: Data for personnel engaged in R&D relate to 1984.
Malaysia: Data for qualified manpower relate to 1982.
Pakistan: Data for personnel engaged in R&D relate to 1988.
Philippines: Data for qualified manpower relate to 1980.
Qatar: Data for qualified manpower relate to 1983.
Singapore: Data for qualified manpower relate to 1980.
Turkey: Data for qualified manpower relate to 1980.

EUROPE

Austria: Data for qualified manpower relate to 1981.
Bulgaria: Data for qualified manpower relate to 1986.
Czechoslovakia: Data for qualified manpower relate to 1980.
Denmark: The number of technicians engaged in R&D includes auxiliary personnel.
Finland: The number of technicians engaged in R&D includes auxiliary personnel.
France: The number of technicians engaged in R&D includes auxiliary personnel.
Germany:
Former German Democratic Republic: Data for qualified manpower relate to 1988. The number of technicians engaged in R&D includes auxiliary personnel.
Greece: Data for qualified manpower relate to 1981.
Hungary: Data for qualified manpower relate to 1984. The number of technicians engaged in R&D includes skilled workers.
Iceland: The number of technicians engaged in R&D include auxiliary personnel.
Ireland: Data for qualified manpower relate to 1981.
Italy: Data for qualified manpower relate to 1981.
Netherlands: Data for qualified manpower relate to 1985. The number of technicians engaged in R&D includes auxiliary personnel.
Norway: Data for qualified manpower relate to 1987. The number of technicians engaged in R&D includes auxiliary personnel.
Poland: Data for qualified manpower relate to 1984.
Sweden: The number of technicians engaged in R&D includes auxiliary personnel.
Switzerland: Data for qualified manpower relate to 1980
Former Yugoslavia: Data for qualified manpower relate to 1988.

OCEANIA

Australia: Data for qualified manpower relate to 1986.

FORMER USSR

Former USSR: Data for qualified manpower relate to 1987.
Belarus: Data for qualified manpower relate to 1986.
Ukraine. Data for qualified manpower relate to 1986.

TABLE 4
TOTAL EXPENDITURE FOR THE PERFORMANCE OF RESEARCH AND EXPERIMENTAL DEVELOPMENT BY SOURCE OF FUNDS

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY		SOURCE OF FUNDS: ALL SOURCES OF FUNDS ('000s)	GOVERNMENT FUNDS ('000s)	PRODUCTIVE ENTERPRISE FUNDS AND SPECIAL FUNDS ('000s)	FOREIGN FUNDS ('000s)	OTHER FUNDS ('000s)
AFRICA								
BURUNDI†	1989	FRANC		536 187	211 064	—	325 123	—
			%	100	39.4	—	60.6	—
CENTRAL AFRICAN REPUBLIC†	1984	FRANC C.F.A.		680 791	406 684	144 515	75 592	54 000
			%	100	59.7	21.2	11.1	7.9
CONGO†	1984	FRANC C.F.A.		25 530	17 575	6 500	1 455	—
			%	100	68.8	25.5	5.7	—
MAURITIUS†	1989	RUPEE		54 300	19 000	1 300	—	34 000
			%	100	35 0	2.4	—	62.6
NIGERIA†	1987	NAIRA		ooo	86 270	ooo	ooo	ooo
RWANDA†	1984	FRANC		235 540	189 040	—	46 500	—
			%	100	80.3	—	19.7	—
SEYCHELLES†	1983	RUPEE		12 854	6 274	—	6 580	—
			%	100	48.8	—	51.2	—
AMERICA, NORTH								
CANADA†	1989	DOLLAR		*8 568 000	*3 170 000	*3 583 000	*907 000	*908 000
			%	100	*37.0	*41.8	*10.6	*10.6
COSTA RICA	1986	COLON		612 000	562 000	./.	50 000	—
			%	100	91.8	./.	8.2	—
CUBA†	1985	PESO		182 478	176 791	—	5 687	—
			%	100	96 9	—	3.1	—
EL SALVADOR†	1989	COLON		ooo	290 881	—	ooo	—
GUATEMALA†	1988	QUETZAL		31 859	11 692	170	5 430	14 567
			%	100	36.7	0.5	17.0	45.7
MEXICO†	1989	PESO		1 050 283	997 720	52 563	→	→
			%	100	95.0	5.0	→	→
NICARAGUA†	1987	CORDOBA		*988 970	*799 470	—	*189 500	—
			%	100	*80.8	—	*19.2	—
PANAMA	1986	BALBOA		173	173	—	—	—
			%	100	100.0	—	—	—
TRINIDAD AND TOBAGO	1984	DOLLAR		143 257	131 005	6 276	4 090	1 886
			%	100	91.4	4.4	2.9	1.3

TABLE 4 cont.
TOTAL EXPENDITURE FOR THE PERFORMANCE OF RESEARCH AND EXPERIMENTAL DEVELOPMENT BY SOURCE OF FUNDS

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY		SOURCE OF FUNDS: ALL SOURCES OF FUNDS ('000s)	GOVERNMENT FUNDS ('000s)	PRODUCTIVE ENTERPRISE FUNDS AND SPECIAL FUNDS ('000s)	FOREIGN FUNDS ('000s)	OTHER FUNDS ('000s)
AMERICA, NORTH cont.								
UNITED STATES†	1988	DOLLAR		135 231 000	62 136 000	67 855 000	—	5 240 000
			%	100	45.9	50.2	—	3.9
AMERICA, SOUTH								
ARGENTINA	1988	AUSTRAL		3 466 700	2 946 700	277 300	69 300	173 400
			%	100	85.0	8.0	2.0	5.0
BRAZIL	1982	CRUZEIRO		*305 500 000	*204 300 000	*60 500 000	16 100 000	24 600 000
			%	100	*66 9	*19.8	*5.3	*8.1
CHILE†	1988	PESO		23 161 300	16 308 900	4 218 200	757 500	1 876 700
			%	100	70.4	18.2	3.3	8.1
PERU†	1984	SOL		159 024 000	76 289 000	43 255 000	33 367 000	6 113 000
			%	100	48.0	27.2	21.0	3.8
ASIA								
CYPRUS†	1984	POUND		1 173	1 159	—	14	—
			%	100	98.8	—	1.2	—
INDIA	1988	RUPEE		34 718 100	31 080 240	3 637 860	./.	./.
			%	100	89.5	10.5	./.	./.
ISRAEL†	1983	SHEKEL		56 300	35 934	12 223	./.	8 143
			%	100	63.8	21.7	./.	14.5
JAPAN†	1988	YEN		10 627 572	2 117 781	8 501 469	8 323	—
			%	100	19.9	80.0	0.1	—
KOREA, REPUBLIC OF†	1988	WON		2 347 000	416 000	1 922 000	—	9 000
			%	100	17.7	81.9	—	0 4
KUWAIT†	1984	DINAR		71 163	24 437	45 736	—	990
			%	100	34.3	64.3	—	1.4
PAKISTAN†	1987	RUPEE		5 582 081	5 582 081	—	—	—
			%	100	100.0	—	—	—
PHILIPPINES†	1984	PESO		612 750	373 290	144 860	79 740	14 860
			%	100	60.9	23.6	13.0	2.4
QATAR	1986	RIYAL		6 650	6 650	—	—	—
			%	100	100.0	—	—	—
SINGAPORE†	1987	DOLLAR		ooo	145 448	223 389	ooo	5 907
SRI LANKA	1984	RUPEE		256 799	214 960	→	41 839	—
			%	100	83.7	→	16.3	—

TABLE 4 cont.

TOTAL EXPENDITURE FOR THE PERFORMANCE OF RESEARCH AND EXPERIMENTAL DEVELOPMENT BY SOURCE OF FUNDS

				SOURCE OF FUNDS				
COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY		ALL SOURCES OF FUNDS ('000s)	GOVERNMENT FUNDS ('000s)	PRODUCTIVE ENTERPRISE FUNDS AND SPECIAL FUNDS ('000s)	FOREIGN FUNDS ('000s)	OTHER FUNDS ('000s)
ASIA cont.								
THAILAND	1987	BAHT		2 664 380	1 825 780	259 450	387 550	191 600
			%	100	68.5	9.7	14.5	7.2
EUROPE								
AUSTRIA	1990	SCHILLING		*24 281 600	*11 293 400	*12 361 200	*561 500	*65 500
			%	100	*46.5	*50.9	*2.3	*0.3
BELGIUM†	1988	FRANC		91 265 100	24 377 200	65 327 800	931 000	629 100
			%	100	26.7	71.6	1.0	0.7
BULGARIA	1989	LEV		1 042 400	433 600	608 800	—	—
			%	100	41.6	58.4	—	—
CZECHOSLOVAKIA†	1987	KORUNA		24 684 000	9 505 000	15 179 000	—	—
			%	100	38 5	61.5	—	—
DENMARK	1989	KRONE		11 892 000	5 408 000	5 573 000	368 000	543 000
			%	100	45.5	46.9	3.1	4.6
FINLAND†	1989	MARKKA		7 207 800	1 800 800	5 322 300	58 400	26 300
			%	25.0	73.8	0.8	0.4	
FRANCE	1987	FRANC		121 364 000	63 021 000	50 785 000	7 171 000	387 000
			%	100	51.9	41.8	5 9	0.3
GERMANY†								
FORMER GDR†	1989	DDR MARK		11 880 000	3 204 000	8 676 000	—	./.
			%	100	27.0	73.0	—	./.
FEDERAL REPUBLIC OF GERMANY†	1987	DEUTSCHE MARK		57 241 000	19 861 000	36 404 000	738 000	238 000
			%	100	34.7	63.6	1.3	0.4
GREECE	1986	DRACHMA		18 331 000	13 646 000	4 248 000	437 000	—
			%	100	74 4	23.2	2.4	—
HUNGARY†	1989	FORINT		33 441 000	8 477 000	24 252 000	226 000	486 000
			%	100	25.3	72.5	0.7	1.5
ICELAND	1989	KRONA		3 123 000	2 186 100	718 290	93 690	124 920
			%	100	70.0	23.0	3 0	4.0
IRELAND	1988	POUND		185 800	85 600	100 200	→	→
			%	100	46.1	53.9	→	→
ITALY†	1988	LIRA		13 281 284	6 883 493	5 834 146	563 645	—
			%	100	51.8	43.9	4.2	—

TABLE 4 cont.

TOTAL EXPENDITURE FOR THE PERFORMANCE OF RESEARCH AND EXPERIMENTAL DEVELOPMENT BY SOURCE OF FUNDS

					SOURCE OF FUNDS			
COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY		ALL SOURCES OF FUNDS ('000s)	GOVERNMENT FUNDS ('000s)	PRODUCTIVE ENTERPRISE FUNDS AND SPECIAL FUNDS ('000s)	FOREIGN FUNDS ('000s)	OTHER FUNDS ('000s)
EUROPE cont.								
MALTA†	1988	LIRA		10	10	—	—	—
			%	100	100.0	—	—	—
NETHERLANDS†	1988	GUILDER		10 163 000	4 328 000	5 431 000	232 000	172 000
			%	100	42.6	53 4	2.3	1.7
NORWAY	1989	KRONE		*12 000 000	*5 800 000	*5 700 000	*200 000	*300 000
			%	100	*48.3	*47.5	*1.7	*2 5
PORTUGAL	1988	ESCUDO		29 910 800	19 006 000	8 185 300	795 900	1 923 600
			%	100	63.5	27.4	2.7	6 4
ROMANIA	1989	LEU		20 866 000	1 100 000	19 766 000	—	—
			%	100	5.3	94.7	—	—
SPAIN	1988	PESETA		287 688 658	140 444 476	136 714 972	7 267 720	3 261 490
			%	100	48.8	47.5	2.5	1.1
SWEDEN†	1987	KRONA		30 554 000	11 297 000	18 662 000	481 000	114 000
			%	100	37.0	61.1	1 6	0 4
SWITZERLAND	1986	FRANC		ooo	1 481 000	5 534 000	ooo	ooo
UNITED KINGDOM†	1989	POUND		11 531 700	4 213 800	5 809 400	1 138 400	370 200
		STERLING	%	100	36.5	50.4	9.9	3.2
FORMER YUGOSLAVIA†	1989	DINAR		2 152 032	772 324	1 153 094	76 073	150 541
			%	100	35.9	53.6	3.5	7.0
OCEANIA								
AUSTRALIA	1988	DOLLAR		4 187 100	2 314 700	1 722 200	56 400	93 900
			%	100	55.3	41.1	1.4	2 2
FIJI†	1986	DOLLAR		3 800	2 800	—	1 000	—
			%	100	73.7	—	26.3	—
FRENCH POLYNESIA†	1983	FRANC C.F.P.		324 720	269 950	3 820	—	50 950
			%	100	83.1	1.2	—	15.7
GUAM†	1989	US DOLLAR		ooo	*1 706	ooo	ooo	*220
NEW CALEDONIA†	1983	FRANC C F.P.		83 000	61 500	21 500	—	—
			%	100	74.1	25.9	—	—
TONGA†	1980	PA'ANGA		426	106	—	320	—
			%	100	24.9	—	75.1	—

TABLE 4

GENERAL NOTES

— MAGNITUDE NIL

ooo DATA NOT AVAILABLE

* PROVISIONAL OR ESTIMATED DATA

./. DATA INCLUDED ELSEWHERE IN ANOTHER CATEGORY

→ THE FIGURE TO THE IMMEDIATE LEFT INCLUDES THE DATA FOR THE COLUMN(S) IN WHICH THIS SYMBOL APPEARS

† COUNTRY NOTES

AFRICA

Burundi: Not including data for the productive sector nor labour costs at the Ministry of Public Health.
Central African Republic: Not including data for the general service sector.
Congo: Not including military and defence R&D.**Mauritius:** Data refer to current expenditure only.
Nigeria: Data relate only to 23 out of 26 national research institutes under the Federal Ministry of Science and Technology.
Rwanda: Not including data for the productive sector.
Seychelles: Not including military and defence R&D.

AMERICA, NORTH

Canada: Not including data for social sciences and humanities in the productive sector (integrated R&D).
Cuba: Not including military and defence R&D.
El Salvador: Not including data for the higher education sector.
Guatemala: Data refer to the productive sector (integrated R&D) and the higher education sector only.
Mexico: Figures in millions.
Nicaragua: Data refer to current expenditure only. Not including military and defence R&D.
United States: Data refer to current expenditure only. Not including data for law, humanities and education.

AMERICA, SOUTH

Chile: Not including military and defence R&D.
Peru: Data refer to the budget allotment for science and technology.

ASIA

Cyprus: Not including data for the productive sector.
Israel: Not including data for humanities and law financed by the universities' current budgets.
Japan: Figures in millions. Not including data for social sciences and humanities in the productive sector (integrated R&D).
Korea, Republic of: Figures in millions. Not including military and defence R&D nor social sciences and humanities.
Kuwait: Data refer to scientific and technological activities (STA).
Pakistan: Data relate to R&D activities concentrated mainly in government-financed research establishments only; social sciences and humanities in the higher education and general service sectors are excluded. Not including military and defence R&D.
Philippines: Not including 670 000 pesos for which a distribution by source of funds is not available.
Singapore: Not including social sciences and humanities.

EUROPE

Belgium: Not including data from communities and regions.
Czechoslovakia: Of military R&D, only that part carried out in civil establishments is included.
Finland: Not including 1 680 million markkas in the higher education sector for which a distribution by source of funds is not available.
Germany:
Former German Democratic Republic: Data refer to current expenditure for science and technology.
Federal Republic of Germany: Due to methodological changes, data are not comparable with the previous years. Not including data for social sciences and humanities in the productive sector.
Hungary: Of military R&D, only that part carried out in civil establishments is included.
Italy: Figures in millions.
Malta: Data relate to the higher education sector only.
Netherlands: Not including data for social sciences and humanities in the productive sector (integrated R&D).
Sweden: Not including data for social sciences and humanities in the productive and general service sectors.
United Kingdom: Not including funds for R&D performed abroad.
Former Yugoslavia: Figures in millions. Not including military and defence R&D.

OCEANIA

Fiji: Data relate to one research institute only.
French Polynesia: Data relate to one research institute only.
Guam: Data refer to current expenditure in the higher education sector only.
New Caledonia: Data relate to two research institutes only.
Tonga: Data relate to one research institute only.

TABLE 5
CURRENT EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT BY TYPE OF R&D ACTIVITY

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY		CURRENT EXPENDITURE BY TYPE OF R&D ACTIVITY: ALL TYPES OF R&D ACTIVITY ('000s)	FUNDAMENTAL RESEARCH ('000s)	APPLIED RESEARCH ('000s)	EXPERIMENTAL DEVELOPMENT ('000s)
AFRICA							
BURUNDI†	1989	FRANC		536 187	42 883	493 304	→
			%	100	8.0	92.0	→
SEYCHELLES†	1983	RUPEE		6 083	—	5 400	683
			%	100	—	88.8	11.2
AMERICA, NORTH							
CUBA†	1985	PESO		182 478	29 197	140 508	12 773
			%	100	16.0	77.0	7.0
MEXICO†	1989	PESO		1 050 283	216 319	475 408	358 556
			%	100	20.6	45 3	34.1
UNITED STATES†	1988	DOLLAR		135 231 000	18 460 000	30 897 000	85 874 000
			%	100	13.7	22.8	63.5
AMERICA, SOUTH							
ARGENTINA	1988	AUSTRAL		2 724 800	940 100	1 618 500	166 200
			%	100	34.5	59.4	6.1
ASIA							
JAPAN†	1988	YEN		9 759 566	1 347 078	2 361 349	6 051 139
			%	100	13.8	24.2	62.0
JORDAN†	1986	DINAR		5 587	1 388	2 701	1 498
			%	100	24.8	48 3	26.8
KOREA, REPUBLIC OF†	1981	WON		293 131 000	70 367 000	84 283 000	138 481 000
			%	100	24.0	28.8	47.2
PHILIPPINES†	1984	PESO		612 740	88 950	322 770	201 020
			%	100	14.5	52.7	32.8
SINGAPORE†	1984	DOLLAR		144 700	4 900	37 900	101 900
			%	100	3 4	26.2	70.4
SRI LANKA	1984	RUPEE		174 335	17 685	128 535	28 115
			%	100	10.1	73.7	16.1
EUROPE							
AUSTRIA†	1985	SCHILLING		13 468 647	2 938 181	6 411 946	4 118 520
			%	100	21.8	47.6	30.6
BULGARIA	1989	LEV		932 900	132 700	800 200	→
			%	100	14.2	85.8	→
CZECHOSLOVAKIA†	1989	KORUNA		22 100 000	1 402 000	20 698 000	→
			%	100	6.3	93.7	→

TABLE 5 cont.
CURRENT EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT BY TYPE OF R&D ACTIVITY

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY		CURRENT EXPENDITURE BY TYPE OF R&D ACTIVITY: ALL TYPES OF R&D ACTIVITY ('000s)	FUNDAMENTAL RESEARCH ('000s)	APPLIED RESEARCH ('000s)	EXPERIMENTAL DEVELOPMENT ('000s)
EUROPE cont.							
DENMARK†	1989	KRONE		4 872 000	2 068 000	1 994 000	810 000
			%	100	42.4	40.9	16.6
GERMANY†							
FEDERAL REPUBLIC OF GERMANY†	1987	DEUTSCHE MARK		49 578 000	9 576 000	40 002 000	→
			%	100	19.3	80.7	→
HUNGARY†	1989	FORINT		20 993 000	3 555 000	7 906 000	9 532 000
			%	100	16.9	37.7	45.4
IRELAND	1986	POUND		143 252	21 206	61 093	60 953
			%	100	14.8	42.6	42 6
ITALY†	1988	LIRA		13 281 284	2 374 191	5 864 928	5 042 165
			%	100	17.9	44.1	38.0
MALTA†	1983	LIRA		10	—	10	—
			%	100	—	100.0	—
NETHERLANDS†	1989	GUILDER		6 025 000	872 000	1 775 000	3 378 000
			%	100	14.5	29.4	56.1
NORWAY	1987	KRONE		9 104 400	1 251 500	3 259 800	4 593 100
			%	100	13 7	35.8	50.5
POLAND†	1985	ZLOTY		83 801 000	13 857 900	27 826 500	42 116 600
			%	100	16.5	33.2	50.3
PORTUGAL†	1986	ESCUDO		19 867 700	3 734 600	7 777 600	8 355 500
			%	100	18.8	39.1	42.1
SPAIN†	1988	PESETA		224 435 577	39 946 760	92 875 676	91 613 141
			%	100	17.8	41.4	40.8
SWEDEN†	1981	KRONA		12 240 000	3 016 000	2 131 000	7 093 000
			%	100	24.6	17.4	58.0
SWITZERLAND†	1986	FRANC		7 015 000	2 850 000	→	4 165 000
			%	100	40 6	→	59.4
UNITED KINGDOM†	1989	POUND STERLING		6 762 400	323 400	1 877 500	4 561 500
			%	100	4.8	27.8	67 4
FORMER YUGOSLAVIA†	1989	DINAR		1 336 951	329 149	547 063	460 739
			%	100	24.6	40.9	34.5

TABLE 5 cont.
CURRENT EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT BY TYPE OF R&D ACTIVITY

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY		CURRENT EXPENDITURE BY TYPE OF R&D ACTIVITY: ALL TYPES OF R&D ACTIVITY ('000s)	FUNDAMENTAL RESEARCH ('000s)	APPLIED RESEARCH ('000s)	EXPERIMENTAL DEVELOPMENT ('000s)
OCEANIA							
AUSTRALIA†	1988	DOLLAR		4 187 200	1 149 800	1 671 900	1 365 500
			%	100	27.5	39.9	32.6
FRENCH POLYNESIA†	1983	FRANC C.F.P.		324 720	—	324 720	—
			%	100	—	100.0	—
GUAM†	1989	US DOLLAR		*1 926	*1 356	*570	—
			%	100	*70.4	*29.6	—
NEW CALEDONIA†	1983	FRANC C.F.P.		83 000	1 500	—	81 500
			%	100	1.8	—	98.2
TONGA†	1980	PA'ANGA		279	—	279	—
			%	100	—	100.0	—

TABLE 5

GENERAL NOTES

— MAGNITUDE NIL

* PROVISIONAL OR ESTIMATED DATA

→ THE FIGURE TO THE IMMEDIATE LEFT INCLUDES THE DATA FOR THE COLUMN(S) IN WHICH THIS SYMBOL APPEARS

† COUNTRY NOTES

AFRICA

Burundi: Data relate to total expenditure by type of R&D activity in the higher education and general service sectors only and do not include labour costs at the Ministry of Public Health.

Seychelles: Not including military and defence R&D.

AMERICA, NORTH

Cuba: Data refer to total expenditure by type of R&D activity. Not including military and defence R&D.

Mexico: Figures in millions. Data refer to total expenditure by type of R&D activity.

United States: Not including data for law, humanities and education.

ASIA

Japan: Figures in millions. Data refer to total expenditure for R&D activities performed in the natural sciences and engineering institutes, by type of R&D activity.

Jordan: Data refer to total expenditure by type of R&D activity. Not including military and defence R&D.

Korea, Republic of: Data refer to total expenditure by type of R&D activity. Not including military and defence R&D nor social sciences and humanities.

Philippines: Data relate to total expenditure by type of R&D activity. Not including 670 000 pesos for which the distribution by type of R&D activity is not known.

Singapore: Data relate to total expenditure by type of R&D activity in the productive and general service sectors only and do not include social sciences and humanities.

EUROPE

Austria: Not including 429 418 000 schillings disbursed by the provincial hospitals for which a distribution by type of R&D activity is unknown.

Czechoslovakia: Of military R&D, only that part carried out in civil establishments is included.

Denmark: Not including data for the productive sector.

Germany:

Federal Republic of Germany: Not including the relevant part of 644 million Deutsche marks for which a breakdown between current and capital expenditure is not known. Not including social sciences and humanities in the productive sector.

Hungary: The total in first column does not include 8 417 million forints for which a breakdown by type of R&D activity is not available. Of military R&D, only that part carried out in civil establishments is included.

Italy: Figures in millions. Data refer to total expenditure by type of R&D activity.

Malta: Data refer to the higher education sector only.

Netherlands: Data refer to total expenditure by type of R&D activity, in the productive sector (integraded R&D) only. Not including social sciences and humanities.

Poland: Not including military and defence R&D.

Portugal: Data refer to total expenditure by type of R&D activity.

Spain: Not including the relevant part of 2 267 589 000 pesetas for which the distribution between current and capital expenditure is not known

Sweden: Not including social sciences and humanities in the productive and general service sectors.

Switzerland: Data refer to total expenditure by type of R&D activity.

United Kingdom: Data refer only to the productive sector (integrated R&D and some non-integrated R&D). Not including funds for R&D performed abroad.

Former Yugoslavia: Figures in millions. Not including military and defence R&D.

OCEANIA

Australia: Data relate to total expenditure by type of R&D activity.

French Polynesia: Data refer to total expenditure by type of R&D activity at one research institute.

Guam: Data refer to the higher education sector only.

New Caledonia: Data refer to total expenditure by type of R&D activity at two research institutes.

Tonga: Data relate to one research institute only.

TABLE 6
EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

			EXPENDITURE FOR R&D		
				CURRENT EXPENDITURE	
COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY	TOTAL ('000s)	AMOUNT ('000s)	% OF TOTAL
AFRICA					
ALGERIA†	1971	DINAR	77 500	67 500	87.1
	1972		78 000	68 000	87.2
BURUNDI†	1984	FRANC	173 197	ooo	ooo
	1989		536 187	ooo	ooo
EGYPT†	1976	POUND	33 440	26 686	79.8
	1982		40 378	34 242	84.8
GABON†	1984	FRANC C.F.A.	415 000	265 000	63.9
	1985		424 000	274 000	64.6
	1986		380 000	250 000	65.8
MADAGASCAR	1986	FRANC	7 046 815	603 815	8.6
	1987		6 478 136	962 638	14.9
	1988		14 371 515	993 515	6.9
MAURITIUS	1980	RUPEE	36 500	29 700	81.4
	1985		26 000	17 700	68.1
	1989		104 300	54 300	52.1
NIGER†	1974	FRANC C.F.A.	40 140	40 140	100.0
	1975		92 794	92 794	100.0
	1976		141 703	141 703	100.0
NIGERIA†	1985	NAIRA	82 952	72 941	87.9
	1986		80 319	69 965	87.1
	1987		86 270	69 615	80.7
RWANDA	1983	FRANC	283 920	96 400	34.0
	1984		260 750	92 760	35.6
	1985		918 560	99 280	10.8
SEYCHELLES†	1973	RUPEE	402	290	72.1
	1981		1 037	337	32.5
	1983		12 854	6 083	47.3
SUDAN	1972	POUND	2 291	ooo	ooo
	1973		3 012	2 444	81.1
	1978		5 115	4 294	83.9
ZAMBIA	1970	KWACHA	ooo	*1 980	ooo
	1972		6 261	4 726	75.5

TABLE 6 cont.
EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY	EXPENDITURE FOR R&D TOTAL ('000s)	CURRENT EXPENDITURE AMOUNT ('000s)	CURRENT EXPENDITURE % OF TOTAL
AMERICA, NORTH					
CANADA†	1980	DOLLAR	3 491 000	ooo	ooo
	1985		6 709 000	ooo	ooo
	1989		*8 568 000	ooo	ooo
COSTA RICA	1983	COLON	300 000	ooo	ooo
	1985		693 000	ooo	ooo
	1986		612 000	ooo	ooo
CUBA†	1980	PESO	95 889	76 796	80.1
	1985		182 478	138 294	75.8
	1989		222 000	158 691	71 5
EL SALVADOR†	1986	COLON	226 275	ooo	ooo
	1987		258 125	ooo	ooo
	1989		290 881	195 964	67.4
GUATEMALA	1974	QUETZAL	*5 139	*3 721	*72.4
	1978		13 526	ooo	ooo
	1983		44 797	ooo	ooo
JAMAICA†	1984	DOLLAR	5 033	3 390	67.4
	1985		3 605	3 297	91.5
	1986		4 016	3 886	96.8
MEXICO†	1985	PESO	194 842	ooo	ooo
	1988		875 236	ooo	ooo
	1989		1 050 283	ooo	ooo
PANAMA	1974	BALBOA	2 908	2 707	93.1
	1975		3 296	ooo	ooo
ST LUCIA	1982	E. CARIBB. DOLLAR	15 137	ooo	ooo
	1983		13 157	ooo	ooo
	1984		12 150	ooo	ooo
TRINIDAD AND TOBAGO†	1970	DOLLAR	5 171	4 371	84.5
	1984		143 257	109 921	76.7
TURKS AND CAICOS ISLANDS	1973	US DOLLAR	51	ooo	ooo
	1974		8	ooo	ooo
	1984		—	—	—
UNITED STATES†	1980	DOLLAR	63 810 000	62 214 000	97.5
	1985		116 796 000	113 745 000	97.4
	1988		139 255 000	135 231 000	97.1

TABLE 6 cont.
EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

			EXPENDITURE FOR R&D		
				CURRENT EXPENDITURE	
COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY	TOTAL ('000s)	AMOUNT ('000s)	% OF TOTAL
AMERICA, SOUTH					
ARGENTINA†	1978	PESO	195 278	136 550	69.9
	1980		1 480 800	1 006 900	68.0
	1981		2 321 932	...	...
BRAZIL†	1983	CRUZEIRO	673 919	...	...
	1984		1 482 604	...	...
	1985		5 390 540	...	...
CHILE†	1983	PESO	7 104 314	...	...
	1985		11 403 365	...	...
	1988		22 205 438	...	...
ECUADOR	1970	SUCRE	90 515	...	...
	1973		142 310	...	...
GUYANA†	1980	DOLLAR	824	...	...
	1982		2 800	...	...
PERU†	1981	SOL	29 508 000	...	...
	1983		83 742 000	...	...
	1984		159 024 000	...	...
URUGUAY	1971	PESO	*1 673	*1 401	*83.7
	1972		1 858	...	...
VENEZUELA†	1980	BOLIVAR	851 280	...	...
	1985		1 411 720	...	...
	1986		1 294 930	...	...
ASIA					
BRUNEI DARUSSALAM†	1980	DOLLAR	4 300	2 900	67.4
	1983		7 560	4 560	60 3
	1984		10 880	8 220	75.6
CYPRUS†	1982	POUND	937	...	...
	1983		1 044	...	...
	1984		1 159	...	...
INDIA†	1980	RUPEE	7 605 200	...	...
	1985		20 687 800	15 585 950	76.2
	1988		34 718 100	29 318 170	84.4
INDONESIA†	1984	RUPIAH	279 000 000	217 980 000	78.1
	1985		242 120 000	203 488 000	84.0
	1988		259 283 000	194 638 000	75.1

TABLE 6 cont.
EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY	EXPENDITURE FOR R&D TOTAL ('000s)	CURRENT EXPENDITURE AMOUNT ('000s)	CURRENT EXPENDITURE % OF TOTAL
ASIA cont.					
IRAN, ISLAMIC REPUBLIC OF†	1972	RIAL	3 531 807	2 246 789	63.6
	1984		21 527 000	11 584 000	53.8
	1985		22 010 713	12 546 398	57.0
IRAQ†	1972	DINAR	2 361	1 794	76.0
	1973		2 310	1 791	77.5
	1974		3 471	2 743	79.0
ISRAEL†	1981	SHEKEL	7 485	ooo	ooo
	1982		19 217	ooo	ooo
	1983		56 300	ooo	ooo
JAPAN†	1980	YEN	5 246 248	4 312 249	82.2
	1985		8 890 299	7 304 291	82.2
	1988		10 627 572	8 943 096	84.2
JORDAN†	1985	DINAR	*5 501	ooo	ooo
	1988		*5 592	ooo	ooo
	1989		*5 583	ooo	ooo
KOREA, REPUBLIC OF†	1980	WON	211 727	162 594	76.8
	1985		1 155 156	642 259	55.6
	1988		2 347 000	1 422 000	60.6
KUWAIT†	1982	DINAR	43 746	40 500	92.6
	1983		67 250	60 616	90.1
	1984		71 163	63 016	88.6
LEBANON†	1978	POUND	ooo	9 400	ooo
	1979		ooo	11 500	ooo
	1980		22 000	ooo	ooo
MALAYSIA†	1988	RINGGIT	87 100	ooo	ooo
	1989		97 200	ooo	ooo
PAKISTAN†	1984	RUPEE	3 834 287	2 293 617	59.8
	1985		4 200 325	2 788 753	66.4
	1987		5 582 081	ooo	ooo
PHILIPPINES†	1980	PESO	623 000	474 030	76.1
	1983		514 590	439 680	85.4
	1984		613 410	514 800	83.9
QATAR	1984	RIYAL	13 910	8 300	59.7
	1985		7 120	6 520	91.6
	1986		6 650	6 650	100.0

TABLE 6 cont.
EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

			EXPENDITURE FOR R&D		
				CURRENT EXPENDITURE	
COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY	TOTAL ('000s)	AMOUNT ('000s)	% OF TOTAL
ASIA cont.					
SINGAPORE†	1981	DOLLAR	81 900	59 350	72.5
	1984		214 300	160 000	74.7
	1987		374 700	223 700	59.7
SRI LANKA†	1975	RUPEE	45 097	32 662	72.4
	1983		217 608	148 971	68.5
	1984		256 799	174 335	67.9
THAILAND	1983	BAHT	2 126 000	ooo	ooo
	1985		3 473 000	ooo	ooo
	1987		2 664 380	2 120 700	79.6
TURKEY	1984	LIRA	128 885 000	ooo	ooo
	1985		192 465 000	143 315 000	74.5
VIET NAM†	1983	DONG	331 000	ooo	ooo
	1984		516 000	ooo	ooo
	1985		498 000	ooo	ooo
EUROPE					
AUSTRIA	1981	SCHILLING	12 331 026	10 201 527	82.7
	1985		17 182 272	13 898 065	80.9
	1990		*24 281 600	ooo	ooo
BELGIUM†	1985	FRANC	79 831 700	ooo	ooo
	1987		87 788 600	ooo	ooo
	1988		91 265 100	ooo	ooo
BULGARIA	1980	LEV	470 800	407 800	86.6
	1985		812 300	716 500	88.2
	1989		1 042 400	932 900	89.5
CZECHOSLOVAKIA†	1980	KORUNA	18 302 000	15 979 000	87.3
	1985		21 298 000	18 477 000	86.8
	1989		24 721 000	22 100 000	89.4
DENMARK	1981	KRONE	4 484 000	4 038 000	90.1
	1985		7 692 000	6 513 000	84.7
	1989		11 892 000	10 517 000	88.4
FINLAND†	1981	MARKKA	2 595 000	2 310 000	89.0
	1985		*5 214 000	ooo	ooo
	1989		*8 887 800	6 114 400	84.8

TABLE 6 cont.
EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY	EXPENDITURE FOR R&D TOTAL ('000s)	CURRENT EXPENDITURE AMOUNT ('000s)	CURRENT EXPENDITURE % OF TOTAL
EUROPE cont.					
FRANCE	1981	FRANC	62 472 000	56 858 000	91.0
	1985		105 917 000	95 152 000	89.8
	1988		130 631 000	117 729 000	89.4
GERMANY†					
FORMER GDR†	1987	DDR MARK	ooo	11 476 000	ooo
	1988		ooo	11 892 000	ooo
	1989		ooo	11 880 000	ooo
FED. REP. OF GERMANY†	1979	DEUTSCHE MARK	32 869 000	28 523 000	88.4
	1985		49 519 000	43 096 000	87.6
	1987		57 240 000	49 578 000	87.6
GREECE†	1981	DRACHMA	4 039 000	ooo	ooo
	1982		5 019 000	ooo	ooo
	1983		6 067 000	ooo	ooo
HUNGARY†	1980	FORINT	21 258 000	18 211 000	85.7
	1985		24 077 000	20 767 000	86.3
	1989		33 441 000	29 410 000	87.9
ICELAND	1981	KRONA	160 000	ooo	ooo
	1985		845 000	ooo	ooo
	1989		3 123 000	ooo	ooo
IRELAND	1981	POUND	83 332	73 003	87.6
	1985		146 702	125 335	85.4
	1988		185 800	ooo	ooo
ITALY†	1980	LIRA	2 897 274	2 442 501	84.3
	1985		9 132 902	7 373 662	80.7
	1988		13 281 284	11 423 405	86.0
MALTA†	1983	LIRA	10	9	90.0
	1985		10	9	90 0
	1988		10	9	90.0
NETHERLANDS†	1980	GUILDER	6 348 000	5 731 000	90.3
	1985		8 748 000	7 801 000	89.2
	1989		10 283 000	9 105 000	88.5
NORWAY	1980	KRONE	3 629 800	3 307 200	91.1
	1985		8 109 900	7 276 700	89.7
	1989		*12 000 000	*10 700 000	*89.2

TABLE 6 cont.
EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY	EXPENDITURE FOR R&D TOTAL ('000s)	CURRENT EXPENDITURE AMOUNT ('000s)	CURRENT EXPENDITURE % OF TOTAL
EUROPE cont.					
POLAND†	1980	ZLOTY	42 400 000	37 400 000	88.2
	1985		100 396 900	83 801 000	83.5
	1987		257 321 000	220 704 300	85.8
PORTUGAL	1980	ESCUDO	4 118 500	3 160 600	76.7
	1984		11 307 600	9 328 800	82.5
	1988		29 910 800	23 520 300	78.6
ROMANIA	1987	LEU	19 848 000	17 468 000	88.0
	1988		20 415 000	18 010 000	88.2
	1989		20 866 000	18 449 000	88.4
SPAIN†	1980	PESETA	61 110 462	52 316 874	85.6
	1985		155 340 938	126 450 000	81.4
	1988		287 688 658	224 435 577	78.6
SWEDEN†	1981	KRONA	13 320 000	12 240 000	91.9
	1985		24 989 000	22 365 000	89.5
	1991		36 410 000	ooo	ooo
SWITZERLAND	1977	FRANC	*3 430 000	*3 110 000	*90.7
	1980		ooo	3 611 100	ooo
	1983		ooo	4 643 000	ooo
UNITED KINGDOM†	1981	POUND STERLING	5 921 200	ooo	ooo
	1985		7 919 200	ooo	ooo
	1989		11 531 700	ooo	ooo
FORMER YUGOSLAVIA†	1980	DINAR	14 105	ooo	ooo
	1985		94 688	ooo	ooo
	1989		2 152 032	1 336 950	62.1
OCEANIA					
AMERICAN SAMOA†	1970	US DOLLAR	100	80	80.0
	1971		120	100	83.3
AUSTRALIA	1981	DOLLAR	1 561 800	1 365 800	87.5
	1985		2 747 400	2 422 700	88.2
	1988		4 187 100	3 596 900	85.9
FIJI†	1984	DOLLAR	2 260	2 000	88.5
	1985		2 750	2 250	81.8
	1986		3 800	3 000	78.9

TABLE 6 cont.
EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT: SELECTED DATA FOR RECENT YEARS

COUNTRY/ TERRITORY	REFERENCE YEAR	CURRENCY	EXPENDITURE FOR R&D TOTAL ('000s)	CURRENT EXPENDITURE AMOUNT ('000s)	CURRENT EXPENDITURE % OF TOTAL
OCEANIA cont.					
FRENCH POLYNESIA†	1980	FRANC C.F.P.	236 990	230 970	97.5
	1982		304 320	301 650	99.1
	1983		324 720	308 440	95.0
GUAM†	1984	US DOLLAR	431	ooo	ooo
	1985		418	ooo	ooo
	1986		502	ooo	ooo
NEW CALEDONIA†	1983	FRANC C.F.P.	184 224	154 924	84.1
	1984		484 741	456 485	94.2
	1985		800 820	707 547	88.4
NEW ZEALAND†	1975	DOLLAR	*99 776	*91 449	*91.7
	1977		117 322	110 936	94.6
	1979		175 373	157 768	90.0
PACIFIC ISLANDS	1978	US DOLLAR	185	185	100.0
	1979		185	185	100.0
SAMOA	1976	TALA	1 385	380	27.4
	1977		2 341	341	14.6
	1978		2 500	500	20.0
TONGA†	1978	PA'ANGA	240	226	94.2
	1979		475	256	53.9
	1980		426	279	65.5
VANUATU	1973	FRANC	13 119	13 119	100.0
	1974		20 925	20 925	100.0
	1975		21 603	21 603	100.0
FORMER USSR					
FORMER USSR†	1980	ROUBLE	21 300 000	ooo	ooo
	1985		28 600 000	ooo	ooo
	1988		37 800 000	ooo	ooo

TABLE 6

GENERAL NOTES

— MAGNITUDE NIL

ooo DATA NOT AVAILABLE

* PROVISIONAL OR ESTIMATED DATA

† COUNTRY NOTES

AFRICA

Algeria: Data relate to the higher education sector only.
Burundi: Not including data for the productive sector. In 1989, labour costs at the Ministry of Public Health are also excluded.
Egypt: Not including military and defence R&D.
Gabon: Not including data for the productive sector.
Niger: Data relate to the higher education sector only.
Nigeria: Data relate only to 23 out of 26 national research institutes under the Federal Ministry of Science and Technology.
Seychelles: Not including military and defence R&D.

AMERICA, NORTH

Canada: Not including social sciences and humanities in the productive sector (integrated R&D).
Cuba: Not including military and defence R&D. Data for 1989 refer to government funds only.
El Salvador: Data relate to R&D activities performed in public enterprises and do not include higher education sector nor foreign funds.
Jamaica: Data relate to the Scientific Research Council only.
Mexico: Figures in millions.
Trinidad and Tobago: Data for 1970 do not include law, education and arts.
United States: Not including data for law, humanities and education. Total expenditure does not include capital expenditure in the productive sector. In 1980, capital expenditure for R&D in private non-profit organizations is also excluded.

AMERICA, SOUTH

Argentina: Figures in millions.
Brazil: Figures in millions. Not including private productive enterprises.
Chile: Not including military and defence R&D.
Guyana: Not including military and defence R&D. Data for the general service sector and for medical sciences in the higher education sector are also excluded.
Peru: Data refer to the budget allotment for science and technology.
Venezuela: Data refer to government funds only and do not include military and defence R&D.

ASIA

Brunei Darussalam: Data relate to two research institutes only.
Cyprus: Data do not include the productive sector and refer to government funds only.
India: For 1985, the total expenditure includes 243 700 000 rupees in the higher education sector for which a distribution between current and capital expenditure is not available. This figure has been excluded from the percentage calculation.
Indonesia: Data refer only to government expenditure in the general service sector.
Iran, Islamic Republic of: Data refer to government expenditure only.
Iraq: Partial data. In 1974, expenditure for R&D in government departments concerned only with scientific activities was 7 409 000 dinars of which 4 909 000 dinars were current expenditure.
Israel: Not including data for humanities and law financed by the universities' current budgets.
Japan: Figures in millions. Not including data for social sciences and humanities in the productive sector (integrated R&D).
Jordan: Not including military and defence R&D.
Korea, Republic of: Figures in millions. Not including military and defence R&D. Data for 1980 exclude law, humanities and education; for 1985 and 1988 not including social sciences and humanities.
Kuwait: Data refer to scientific and technological activities (STA).
Lebanon: Partial data referring to the Faculty of Science at the University of Lebanon only.
Malaysia: Data relate to government expenditure only.
Pakistan: Data refer to R&D activities which are concentrated mainly in government-financed research establishments. Social sciences and humanities in the higher education and general service sectors are not included. Not including military and defence R&D.
Philippines: Not including private non-profit organizations in 1980.
Singapore: In 1987, not including foreign funds nor social sciences and humanities.
Sri Lanka: For 1975 data do not include capital expenditure in the higher education sector.
Viet Nam: Data refer to government expenditure only.

EUROPE

Belgium: Not including communities and regions.
Czechoslovakia: Of military R&D, only that part carried out in civil establishments is included.
Finland: For 1989, total expenditure includes 1 680 million markkas in the higher education sector for which a distribution between current and capital expenditure is not available. This figure has been excluded from the percentage calculation.
Germany:
Former German Democratic Republic: Data refer to 'expenditure for science and technology'.
Federal Republic of Germany: For 1979, 1985 and 1987, total expenditure includes respectively 615, 350 and 644 million Deutsche marks for which a distribution between current and capital expenditure is not available. These figures have been excluded from the percentage calculations. Not including social sciences and humanities in the productive sector.
Greece: Data relate to government activities only.
Hungary: Due to methodological changes, data since 1981 are not comparable with the previous years. Of military R&D, only that part carried out in civil establishments is included.
Italy: Figures in millions.
Malta: Data relate to the higher education sector only.
Netherlands: Not including social sciences and humanities in the productive sector (integrated R&D).
Poland: Not including military and defence R&D.
Spain: For 1988, total expenditure includes 2 267 589 000 pesetas (disbursed by the private non-profit organizations) for which a distribution between current and capital expenditure is not available; this figure has been excluded from the percentage calculation.
Sweden: Not including social sciences and humanities in the productive and general service sectors.
United Kingdom: Not including funds for R&D performed abroad. Data for 1981 and 1985 exclude social sciences and humanities.
Former Yugoslavia: Figures in millions. Not including military and defence R&D.

OCEANIA

American Samoa: Data relate to one research institute only.
Fiji: Data relate to one research institute only.
French Polynesia: Data relate to one research institute only.
Guam: Data relate to the higher education sector only.
New Caledonia: Data refer to the following number of research institutes: In 1983: three; in 1984: four; in 1985: six.
New Zealand: In 1977 total expenditure excludes capital expenditure for buildings.
Tonga: Data relate to one research institute only.

FORMER USSR

Former USSR: 'Expenditure on science' from the national budget and other sources.

TABLE 7
SELECTED INDICATORS FOR EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT

COUNTRY/ TERRITORY	YEAR	CURRENCY	EXPENDITURE FOR R&D: AS % OF GROSS NATIONAL PRODUCT (GNP)	PER CAPITA (IN NATIONAL CURRENCY)	ANNUAL AVERAGE PER R&D SCIENTIST OR ENGINEER (IN NATIONAL CURRENCY)
AFRICA					
BENIN	1989	FRANC C.F.A.	0.7	745.3	4 216 200
BURUNDI	1989	FRANC	0.3	101.0	3 154 000
CENTRAL AFRICAN REPUBLIC	1984	FRANC C.F.A.	0.2	264.4	3 473 400
CONGO	1984	FRANC C.F.A.	0.0	13.6	29 600
EGYPT	1982	POUND	0.2	0.9	ooo
GABON	1986	FRANC C.F.A.	0.0	380.0	1 900
LIBYAN ARAB JAMAHIRIYA	1980	DINAR	0.2	7.5	20 800
MADAGASCAR	1988	FRANC	0.4	1 276.3	*53 425 700
MAURITIUS	1989	RUPEE	0.3	97.3	540 400
NIGERIA	1987	NAIRA	0.1	0.9	64 500
RWANDA	1985	FRANC	0.5	150.5	12 937 500
SEYCHELLES	1983	RUPEE	1.3	200.8	714 100
AMERICA, NORTH					
CANADA	1989	DOLLAR	*1.4	*326.0	*140 200
COSTA RICA	1986	COLON	0.3	225.5	ooo
CUBA	1989	PESO	0.8	21.1	18 400
EL SALVADOR	1989	COLON	0.9	56.3	2 048 500
GUATEMALA	1988	QUETZAL	0.2	3.7	37 100
JAMAICA	1986	DOLLAR	0.0	1.7	223 100
MEXICO	1989	PESO	0.2	12 107.6	ooo
NICARAGUA	1987	CORDOBA	0.0	282.5	1 364 100
PANAMA	1986	BALBOA	0.0	0.1	ooo
ST LUCIA	1984	E. CARIBB. DOLLAR	2.9	90.7	229 200
TRINIDAD AND TOBAGO	1984	DOLLAR	0.8	123.5	520 900
UNITED STATES	1988	DOLLAR	2.9	568.4	*146 700
AMERICA, SOUTH					
ARGENTINA	1988	AUSTRAL	0.4	110.0	312 700
BRAZIL	1985	CRUZEIRO	0.4	39 763.8	101 971 900
CHILE	1988	PESO	0.5	1 757.6	4 838 800
COLOMBIA	1982	PESO	0.1	98.0	2 543 200
GUYANA	1982	DOLLAR	0.2	3.6	31 500
PERU	1984	SOL	0.2	8 373.7	ooo
VENEZUELA	1985	BOLIVAR	0.3	81.5	ooo
ASIA					
BRUNEI DARUSSALAM	1984	DOLLAR	0.1	50.6	544 000
CYPRUS	1984	POUND	0.1	1.8	23 000
INDIA	1988	RUPEE	0.9	42.4	*291 700
INDONESIA	1988	RUPIAH	0.2	1 461.0	8 093 000
IRAN, ISLAMIC REPUBLIC OF	1985	RIAL	ooo	462.2	6 891 300
ISRAEL	1985	SHEKEL	3.1	215.2	*45 300

TABLE 7 cont.
SELECTED INDICATORS FOR EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT

COUNTRY/ TERRITORY	YEAR	CURRENCY	EXPENDITURE FOR R&D AS % OF GROSS NATIONAL PRODUCT (GNP)	PER CAPITA (IN NATIONAL CURRENCY)	ANNUAL AVERAGE PER R&D SCIENTIST OR ENGINEER (IN NATIONAL CURRENCY)
ASIA cont.					
JAPAN	1988	YEN	2.8	86 901.8	17 284 700
JORDAN	1986	DINAR	0.3	1.6	13 400
KOREA, REPUBLIC OF	1988	WON	1.9	55 756.2	41 506 800
KUWAIT	1984	DINAR	0.9	43.6	47 100
LEBANON	1980	POUND	ooo	8.2	122 200
MALAYSIA	1989	RINGGIT	0.1	5.6	*17 600
PAKISTAN	1987	RUPEE	1.0	50.6	*840 500
PHILIPPINES	1984	PESO	0.1	11.4	127 000
QATAR	1986	RIYAL	0.0	21.7	29 000
SINGAPORE	1987	DOLLAR	0.9	143.1	111 500
SRI LANKA	1984	RUPEE	0.2	16.2	*92 000
THAILAND	1987	BAHT	0.2	50.0	481 000
TURKEY	1985	LIRA	0.7	3 822.9	17 068 600
VIET NAM	1985	DONG	ooo	8.3	24 900
EUROPE					
AUSTRIA	1985	SCHILLING	1.3	2 273.4	*2 258 200
BELGIUM	1988	FRANC	1.7	9 273.0	5 482 700
BULGARIA	1989	LEV	2.7	115.9	ooo
CZECHOSLOVAKIA	1989	KORUNA	3.3	1 583.9	377 600
DENMARK	1989	KRONE	1.6	2 316.6	1 115 400
FINLAND	1989	MARKKA	*1.8	*1 793.3	*785 300
FRANCE	1988	FRANC	2.3	2 348.8	1 134 300
GERMANY					
FORMER GDR	1989	DDR MARK	4.3	728.8	93 200
FEDERAL REPUBLIC OF GERMANY	1987	DEUTSCHE MARK	2.9	937.6	345 600
GREECE	1986	DRACHMA	0.3	1 841.2	ooo
HUNGARY	1989	FORINT	2.0	3 168.3	1 636 800
IRELAND	1986	POUND	1.1	50.8	29 300
ITALY	1988	LIRA	1.1	232 414.8	177 479 000
MALTA	1988	LIRA	0.0	0.0	300
NETHERLANDS	1989	GUILDER	2.2	692.5	ooo
NORWAY	1989	KRONE	*2.0	*2 857.8	*991 700
POLAND	1989	ZLOTY	1.2	32 222.0	37 752 700
PORTUGAL	1988	ESCUDO	0.5	2 917.0	5 977 400
ROMANIA	1989	LEU	2.6	902.9	349 700
SPAIN	1988	PESETA	0.7	7 376.1	9 229 700
SWEDEN	1991	KRONA	2.8	4 308.3	ooo
SWITZERLAND	1989	FRANC	1.8	834.2	582 700
UNITED KINGDOM	1989	POUND STERLING	2.3	201.9	ooo
FORMER YUGOSLAVIA	1988	DINAR	1.4	91 060.5	61 893 400
OCEANIA					
AUSTRALIA	1988	DOLLAR	1.3	255.2	108 600

TABLE 7 cont.
SELECTED INDICATORS FOR EXPENDITURE FOR RESEARCH AND EXPERIMENTAL DEVELOPMENT

COUNTRY/ TERRITORY	YEAR	CURRENCY	EXPENDITURE FOR R&D AS % OF GROSS NATIONAL PRODUCT (GNP)	PER CAPITA (IN NATIONAL CURRENCY)	ANNUAL AVERAGE PER R&D SCIENTIST OR ENGINEER (IN NATIONAL CURRENCY)
OCEANIA cont.					
FIJI	1986	DOLLAR	0.3	5.3	105 600
FRENCH POLYNESIA	1983	FRANC C.F.P.	0.2	1 980.0	19 101 200
GUAM	1989	US DOLLAR	ooo	*16.5	*91 714
NEW CALEDONIA	1985	FRANC C.F.P.	0.6	5 268.6	10 400 300
TONGA	1980	PA'ANGA	0.9	4.4	*38 700
FORMER USSR					
FORMER USSR	1988	ROUBLE	6.5	133.5	24 800

TABLE 7

GENERAL NOTES

In the absence of R&D exchange rates those data which are set out in national currency can be compared, one country with another, by the use of the official exchange rates between national currencies and the US dollar given in Table 8. It should be understood, of course, that these exchange rates do not always reflect the real costs of R&D activities. For the former German Democratic Republic and the former USSR, the figures in the first column refer to expenditure as percentage of the net material product; for Cuba, the figure is calculated as percentage of global social product.

ooo DATA NOT AVAILABLE

* PROVISIONAL OR ESTIMATED DATA

TABLE 8
EXCHANGE RATES

COUNTRY/ TERRITORY	NATIONAL CURRENCY	NATIONAL CURRENCY PER UNITED STATES DOLLAR					
		1980	1982	1984	1986	1988	1989
AFRICA							
ALGERIA	DINAR	3.838	4.592	4.983	4.702	5.915	7.609
ANGOLA	KWANSA	29.918	29.918	29.918	29.918	29.918	29.918
BENIN	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
BOTSWANA	PULA	0.777	1.030	1.298	1.879	1.829	2.015
BURKINA FASO	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
BURUNDI	FRANC	90.00	90.00	119.709	114.171	140.395	158.667
CAMEROON	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
CAPE VERDE	ESCUDO	40.175	58.293	84.878	80.145	72.068	77.978
CENTRAL AFRICAN REPUBLIC	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
CHAD	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
COMOROS	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
CONGO	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
COTE D'IVOIRE	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
DJIBOUTI	FRANC	177.721	177.721	177.721	177.721	177.721	177.721
EGYPT	POUND	0.70	0.70	0.70	0.70	0.70	0.852
EQUATORIAL GUINEA†	FRANC C.F.A.	110.63	219.72	321.52	346.3	297.85	319.01
ETHIOPIA	BIRR	2.07	2.07	2.07	2.07	2.07	2.07
GABON	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
GAMBIA	DALASI	1.721	2.29	3.584	6.938	6.709	7.585
GHANA	CEDI	2.75	2.75	35.986	89.204	202.346	270.00
GUINEA	SYLI	18.969	22.366	24.09	333.453	474.396	591.646
GUINEA-BISSAU	PESO	33.81	39.87	105.29	203.95	1 111.06	1 811.42
KENYA	SHILLING	7.42	10.922	14.414	16.226	17.747	20.573
LESOTHO	MALOTI	0.779	1.086	1.475	2.285	2.273	2.623
LIBERIA	DOLLAR	1.00	1.00	1.00	1.00	1.00	1.00
LIBYAN ARAB JAMAHIRIYA	DINAR	0.296	0.296	0.296	0.315	0.286	0.299
MADAGASCAR	FRANC	211.28	349.74	576.64	676.34	1 407.11	1 603.44
MALAWI	KWACHA	0.812	1.056	1.413	1.861	2.561	2.76
MALI	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
MAURITANIA	OUGUIYA	45.914	51.769	63.803	74.375	75.261	83.051
MAURITIUS	RUPEE	7.684	10.873	13.80	13.466	13.438	15.25
MOROCCO	DIRHAM	3.937	6.023	8.811	9.104	8.209	8.488
MOZAMBIQUE	METICAL	32.40	37.77	42.44	40.43	524.64	744.92
NIGER	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
NIGERIA	NAIRA	0.547	0.674	0.767	1.755	4.537	7.365
RWANDA	FRANC	92.84	92.84	100.172	87.64	76.445	79.977
SAO TOME AND PRINCIPE	DOBRA	34.771	40.999	44.159	38.589	86.343	124.672
SENEGAL	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01
SEYCHELLES	RUPEE	6.392	6.553	7.059	6.177	5.384	5.646
SIERRA LEONE	LEONE	1.05	1.239	2.51	16.092	32.514	59.813
SOMALIA	SHILLING	6.295	10.75	20.019	72.00	170.453	490.675
SOUTH AFRICA	RAND	0.779	1.086	1.475	2.285	2.273	2.623
SUDAN	POUND	0.500	0.952	1.30	2.50	4.50	4.50
SWAZILAND	LILANGENI	0.779	1.085	1.475	2.285	2.273	2.623
TOGO	FRANC C.F.A.	211.28	328.61	436.96	346.3	297.85	319.01

TABLE 8 cont.
EXCHANGE RATES

COUNTRY/ TERRITORY	NATIONAL CURRENCY	NATIONAL CURRENCY PER UNITED STATES DOLLAR 1980	1982	1984	1986	1988	1989
AFRICA cont.							
TUNISIA	DINAR	0.405	0.591	0.777	0.794	0.858	0.949
UGANDA	SHILLING	0.07	0.94	3.60	14.00	106.14	223.09
UNITED REPUBLIC OF TANZANIA	SHILLING	8.197	9.283	15.292	32.698	99.292	143.377
ZAIRE	ZAIRE	2.80	5.75	36.13	59.63	187.07	381.45
ZAMBIA	KWACHA	0.789	0.929	1.813	7.788	8.266	13.814
ZIMBABWE	DOLLAR	0.643	0.759	1.258	1.667	1.806	2.119
AMERICA, NORTH							
ANTIGUA AND BARBUDA	E. CARIBB. DOLLAR	2.70	2.70	2.70	2.70	2.70	2.70
BAHAMAS	DOLLAR	1.00	1.00	1.00	1.00	1.00	1.00
BARBADOS	DOLLAR	2.011	2.011	2.011	2.011	2.011	2.011
BELIZE	DOLLAR	2.00	2.00	2.00	2.00	2.00	2.00
BERMUDA	DOLLAR	1.00	1.00	1.00	1.00	1.00	1.00
CANADA	DOLLAR	1.169	1.234	1.295	1.39	1.231	1.184
COSTA RICA	COLON	8.57	37.407	44.533	55.986	75.805	81.504
CUBA§	PESO	0.71	0.85	0.90	0.793	0.776	0.791
DOMINICA	E. CARIBB. DOLLAR	2.7	2.7	2.70	2.70	2.70	2.70
DOMINICAN REPUBLIC	PESO	1.00	1.00	1.00	2.904	6.113	6.34
EL SALVADOR	COLON	2.50	2.50	2.50	4.852	5.00	5.00
GRENADA	E. CARIBB. DOLLAR	2.70	2.70	2.70	2.70	2.70	2.70
GUATEMALA	QUETZAL	1.00	1.00	1.00	1.875	2.62	2.816
HAITI	GOURDE	5.00	5.00	5.00	5.00	5.00	5.00
HONDURAS	LEMPIRA	2.00	2.00	2.00	2.00	2.00	2.00
JAMAICA	DOLLAR	1.781	1.781	3.943	5.478	5.489	5.745
MEXICO	PESO	22.95	56.4	167.83	611.77	2 273.11	2 461.47
MONTSERRAT	E. CARIBB. DOLLAR	2.70	2.70	2.70	2.70	2.70	2.70
NETHERLANDS ANTILLES	GUILDER	1.80	1.80	1.80	1.80	1.80	1.793
NICARAGUA	CORDOBA	ooo	ooo	ooo	ooo	ooo	ooo
PANAMA	BALBOA	1.00	1.00	1.00	1.00	1.00	1.00
SAINT KITTS AND NEVIS	E. CARIBB. DOLLAR	2.70	2.70	2.70	2.70	2.70	2.70
ST LUCIA	E. CARIBB. DOLLAR	2.70	2.70	2.70	2.70	2.70	2.70
ST VINCENT AND THE GRENADINES	E. CARIBB. DOLLAR	2.70	2.70	2.70	2.70	2.70	2.70
TRINIDAD AND TOBAGO	DOLLAR	2.40	2.40	2.40	3.60	3.844	4.25
UNITED STATES	DOLLAR	1.00	1.00	1.00	1.00	1.00	1.00
AMERICA, SOUTH							
ARGENTINA†	AUSTRAL	184.00	2592.0	0.068	0.943	8.753	423.340
BOLIVIA†	BOLIVIANO	24.52	64.07	3 135.91	1.922	2.350	2.692
BRAZIL	CRUZEIRO	0.053	0.180	1.848	13.654	263.00	2 833.92
CHILE	PESO	39.00	50.909	98.656	193.016	245.048	267.155
COLOMBIA	PESO	47.28	64.085	100.817	194.261	299.174	382.568
ECUADOR	SUCRE	25.00	30.03	62.54	122.78	301.61	526.35
GUYANA	DOLLAR	2.55	3.00	3.832	4.272	10.00	27.159
PARAGUAY	GUARANI	126.00	126.00	201.00	339.17	550 00	1 056.22
PERU	INTI	0.289	0.698	3.467	13.948	128.83	2 666.19
SURINAME	GUILDER	1.785	1.785	1.785	1.785	1.785	1.785

TABLE 8 cont.
EXCHANGE RATES

COUNTRY/ TERRITORY	NATIONAL CURRENCY	NATIONAL CURRENCY PER UNITED STATES DOLLAR					
		1980	1982	1984	1986	1988	1989
AMERICA, SOUTH cont.							
URUGUAY	PESO	9.10	13.91	56.12	151.99	359.44	605.51
VENEZUELA	BOLIVAR	4.293	4.293	7.018	8.083	14.5	34.681
ASIA							
AFGHANISTAN	AFGHANI	44.129	50.6	50.60	50.60	50.60	50.60
BAHRAIN	DINAR	0.377	0.376	0.376	0.376	0.376	0.376
BANGLADESH	TAKA	15.454	22.118	25.354	30.407	31.733	32.27
BHUTAN	NGULTRUM	7.863	9.455	11.363	12.611	13.917	16.226
BRUNEI DARUSSALAM	DOLLAR	2.151	2.149	2.141	2.22	2.013	1.951
CHINA	YUAN	1.498	1.893	2.32	3.453	3.722	3.765
CYPRUS	POUND	0.353	0.475	0.588	0.518	0.467	0.494
HONG KONG	DOLLAR	4.976	6.07	7.818	7.803	7.806	7.807
INDIA	RUPEE	7.863	9.455	11.363	12.611	13.917	16.226
INDONESIA	RUPIAH	626.99	661.42	1 025.94	1 282.56	1 685.7	1 770 06
IRAN, ISLAMIC REPUBLIC OF	RIAL	70.615	83.603	90.297	78.76	68.683	72.015
IRAQ	DINAR	0.295	0.299	0.311	0.311	0.311	0.311
ISRAEL†	SHEKEL	0.005	0.024	0.293	1.488	1.599	1.916
JAPAN	YEN	226.74	249.08	237.52	168.52	128.15	137.96
JORDAN	DINAR	0.298	0.353	0.384	0.35	0.374	0.575
KOREA, REPUBLIC OF	WON	607.43	731.08	805.98	881.45	731.47	671.46
KUWAIT	DINAR	0.27	0.288	0.296	0.291	0.279	0.294
LAO PEOPLE'S DEM. REP.	KIP	10.128	35.00	35.00	95.00	392.012	583.015
LEBANON	POUND	3.44	4.74	6.51	38.37	409.23	496.69
MACAU	PATACA	5.095	6.226	8.045	8.357	8.05	8.05
MALAYSIA	RINGGIT	2.177	2.335	2.344	2.581	2.619	2.709
MALDIVES	RUFIYAA	7.55	7.174	7.05	7.151	8.785	9.041
MONGOLIA†	TUGRIK	2.85	3.27	3.79	3.18	2.95	2.99
MYANMAR	KYAT	6.599	7.79	8.386	7.33	6.395	6.705
NEPAL	RUPEE	12.00	13.244	16.459	21.23	23.289	27.189
OMAN	RIAL	0.345	0.345	0.345	0.382	0.385	0.385
PAKISTAN	RUPEE	9.90	11.848	14.046	16.648	18.003	20.542
PHILIPPINES	PESO	7.511	8.54	16.699	20.386	21.095	21.737
QATAR	RIYAL	3.657	3.64	3.64	3.64	3.64	3.64
SAUDI ARABIA	RIYAL	3.327	3.428	3.524	3.703	3.745	3.745
SINGAPORE	DOLLAR	2.141	2.14	2.133	2.177	2.012	1.95
SRI LANKA	RUPEE	16.534	20.812	25.438	28.017	31.807	36.047
SYRIAN ARAB REPUBLIC	POUND	3.925	3.925	3.925	3.925	11.225	11.225
THAILAND	BAHT	20.476	23.00	23.639	26.299	25.294	25.702
TURKEY	LIRA	76.04	162.55	366.68	674.51	1 422.35	2 121.68
UNITED ARAB EMIRATES	DIRHAM	3.707	3.671	3.671	3.671	3.671	3.671
VIET NAM	DONG	0.21	0.94	1.03	18.00	480.00	3 532.78
YEMEN							
FORMER DEM. YEMEN	DINAR	0.345	0.345	0.345	0.345	0.345	0.345
FORMER YEMEN ARAB REP.	RIAL	4.563	4.563	5.353	9.639	9.772	9.76
EUROPE							
ALBANIA§	LEK	7.00	7.00	7.00	7.00	6.00	6.40

TABLE 8 cont.
EXCHANGE RATES

COUNTRY/ TERRITORY	NATIONAL CURRENCY	NATIONAL CURRENCY PER UNITED STATES DOLLAR 1980	1982	1984	1986	1988	1989
EUROPE cont.							
AUSTRIA	SCHILLING	12.938	17.059	20.009	15.267	12.348	13.231
BELGIUM	FRANC	29.242	45.691	57.783	44.672	36.768	39.404
BULGARIA†	LEV	0.85	0.85	0.98	0.94	0.83	0.84
CZECHOSLOVAKIA†	KORUNA	14.27	13.71	16.61	14.99	14.36	15.05
DENMARK	KRONE	5.636	8.332	10.357	8.091	6.732	7.31
FINLAND	MARKKA	3.73	4.82	6.01	5.07	4.183	4.291
FRANCE	FRANC	4.226	6.572	8.739	6.926	5.957	6.380
GERMANY							
FORMER GDR§	DDR MARK	1.95	2.50	3.05	2.00	1.87	1.79
FED. REP. OF GERMANY	DEUTSCHE MARK	1.818	2.427	2.846	2.171	1.756	1.880
GREECE	DRACHMA	42.617	66.803	112.717	139.981	141.861	162.417
HUNGARY	FORINT	32.532	36.631	48.042	45.832	50.413	59.066
ICELAND	KRONA	4.798	12.352	31.694	41.104	43.014	57.042
IRELAND	POUND	0.487	0.705	0.923	0.743	0.656	0.706
ITALY	LIRA	856.45	1 352.51	1 756.96	1 490.81	1 301.63	1 372.09
LIECHTENSTEIN	SWISS FRANC	1.676	2.03	23.50	1.799	1.463	1.636
LUXEMBOURG	FRANC	29.242	45.691	57.784	44.672	36.768	39.404
MALTA	LIRA	0.345	0.412	0.461	0.393	0.331	0.348
MONACO	FRENCH FRANC	4.226	6.572	8.739	6.926	5.957	6.380
NETHERLANDS	GUILDER	1.988	2.67	3.209	2.45	1.977	2.121
NORWAY	KRONE	4.939	6.454	8.161	7.395	6.517	6.905
POLAND	ZLOTY	44.2	84.8	113.20	175.30	430.50	1 439.20
PORTUGAL	ESCUDO	50.062	79.473	146.39	149.587	143.954	157.458
ROMANIA	LEU	60.35	50.292	71.348	54.159	47.867	50.029
SAN MARINO	LIRA	856.45	1 352.51	1 756.96	1 490.81	1 301.63	1 372.09
SPAIN	PESETA	71.702	109.859	160.761	140.048	116.487	118.378
SWEDEN	KRONA	4.230	6.283	8.272	7.124	6.127	6.447
SWITZERLAND	FRANC	1.676	2.03	2.35	1.799	1.463	1.636
UNITED KINGDOM	POUND STERLING	0.43	0.573	0.752	0.682	0.562	0.611
FORMER YUGOSLAVIA†	DINAR	0.003	0.005	0.015	0.038	0.252	2.876
OCEANIA							
AUSTRALIA	DOLLAR	0.878	0.986	1.14	1.496	1.28	1.265
FIJI	DOLLAR	0.818	0.932	1.083	1.133	1.43	1.483
FRENCH POLYNESIA	FRANC C.F.P.	76.829	119.49	158.902	125.935	108.31	116.003
NEW CALEDONIA	FRANC C.F.P.	76.829	119.49	158.902	125.935	108.31	116.003
NEW ZEALAND	DOLLAR	1.027	1.333	1.764	1.913	1.526	1.672
PAPUA NEW GUINEA	KINA	0.671	0.738	0.899	0.971	0.867	0.859
SAMOA	TALA	0.919	1.207	1.862	2.236	2.08	2.27
SOLOMON ISLANDS	SOL. I. DOLLAR	0.830	0.971	1.274	1.742	2.083	2.293
TONGA	PA'ANGA	0.878	0.986	1.14	1.496	1.28	1.264
VANUATU	VATU	68.292	96.208	99.233	106.076	104.426	116.042
FORMER USSR							
FORMER USSR§	ROUBLE	0.66	0.73	0.85	0.684	0.612	0.633
BELARUS§	ROUBLE	0.66	0.73	0.85	0.684	0.612	0.633
UKRAINE§	ROUBLE	0.66	0.73	0.85	0.684	0.612	0.633

TABLE 8

GENERAL NOTES

This table lists rates of exchange for the figures on expenditure or revenue expressed in notional currencies which appear in Tables 4, 5, 6 and 7. The exchange rates are expressed in terms of the number of units of national currency corresponding to one United States dollar.

For most countries, the data were provided by the International Monetary Fund, and refer to average annual exchange rates.

For the remaining countries (indicated by the symbol §) the exchange rates have been extracted from the *Monthly Bulletin of Statistics* of the United Nations.

ooo DATA NOT AVAILABLE

† COUNTRY NOTES

AFRICA

Equatorial Guinea: Prior to 1986, the national currency refers to the Bipkwele.

AMERICA, SOUTH

Argentina: Prior to 1984, exchange rates are expressed in Australes per million US dollars.
Bolivia: Prior to 1986, exchange rates are expressed in Bolivianos per million US dollars.

ASIA

Mongolia: Prior to 1986, data refer to non-commercial rates applied to tourism and to remittances from outside the rouble area, and have been taken from the *Monthly Bulletin of Statistics* published by the United Nations.

EUROPE

Bulgaria: Prior to 1986, data refer to non-commercial rates applied to tourism and to remittances from outside the rouble area, and have been taken from the *Monthly Bulletin of Statistics* published by the United Nations.

The *World Science Report,* which is planned by UNESCO for publication every other year, will review the current state of science around the world, from an organizational and a substantive point of view.

This present issue is made up of four major parts. The first is a collection of essays which together constitute an informative and thought-provoking review of the state of science and technology in various regions of the world. The second part describes how scientific R&D is organized – who carries it out, where, and with what means. International partnership and cooperation are discussed in Part 3, while the fourth part carries overviews of recent developments in the basic sciences. The *Report* concludes with an appendix of statistical tables on national and regional scientific activity and manpower.

The *World Science Report* is both authoritative and readable. Written by authors recognized in their respective fields, the text is packed with facts, figures and discussion on present-day science. As a source of information, this work is a guide for all those with an interest in the shape of science and technology around the globe, be they decision makers, practitioners of science, active participants or observers.

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