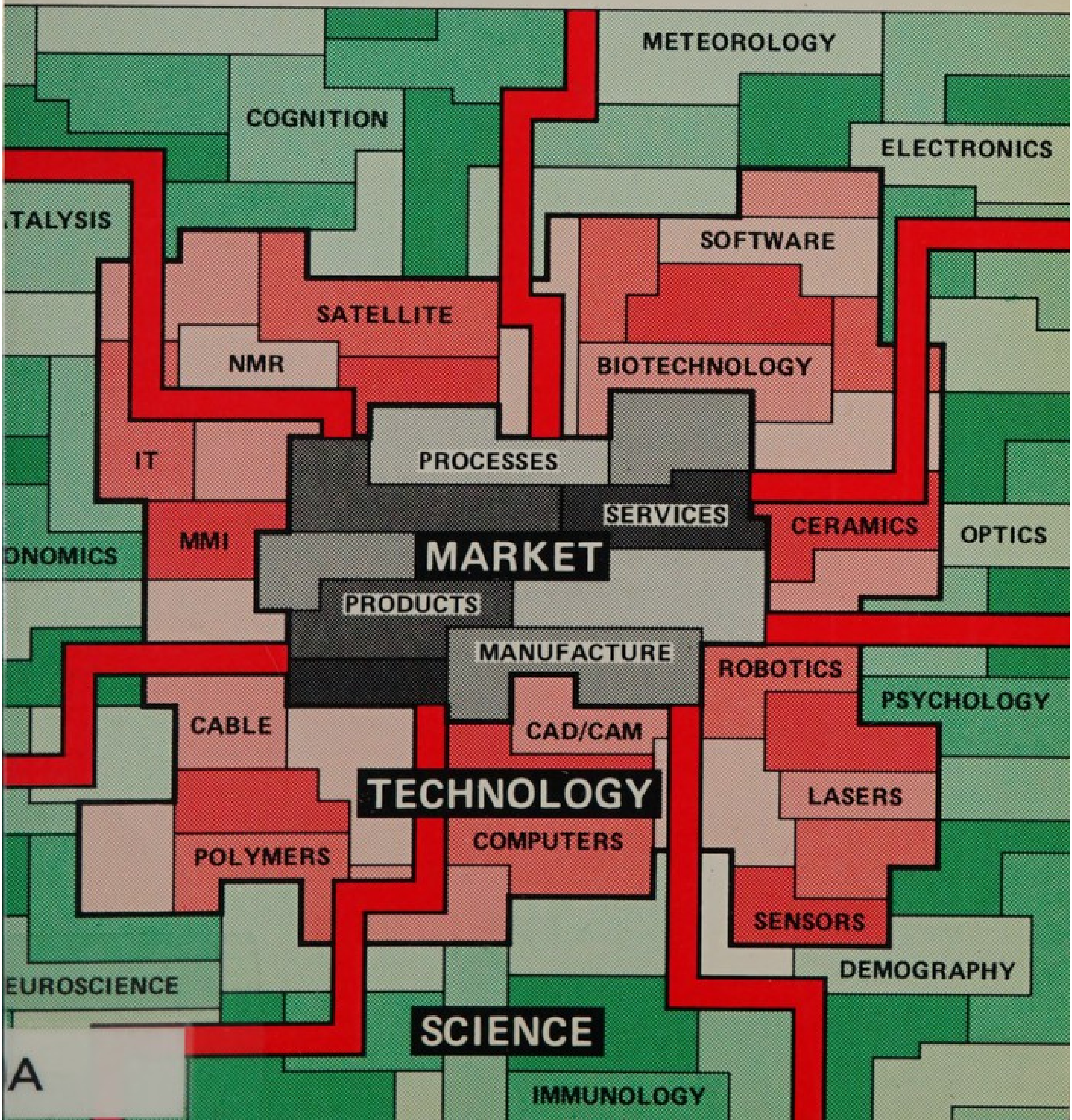
Advisory Council for Applied Research and Development

Exploitable Areas of Science



The Advisory Council for Applied Research and Development (ACARD) has the following terms of reference—

'To advise the Government and publish reports as necessary on—

i. applied research, design and development in the United Kingdom;

ii. the application of research and technology, developed in the United Kingdom and elsewhere, for the benefit of both the public and private sectors in accordance with national economic needs;

iii. the co-ordination, in collaboration with the Advisory Board for Research Councils, of these activities, with research supported through the Department of Education and Science;

iv. the role of the United Kingdom in international collaboration in the field of applied research, design and development related to technology.'

The members of the Council (May 1985) were—

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10 DOWNING STREET

THE PRIME MINISTER

7 October 1985

Dear Sir Henry,

Thank you for your letter of 9 September and the report of the Council on "Exploitable Areas of Science".

I strongly support the main thrust of the report that United Kingdom R & D must be more exploitable and that we ourselves must exploit it better. As the report points out some other countries do seem able to identify the promising new areas with industrial potential sooner than we do and act on them more quickly. I therefore welcome the proposal in the report for improving the UK performance. I agree that the arrangements should be separate from and funded independently of Government but should, nevertheless, have a major influence on R & D supported by Government. Involvement of both the industrial and scientific communities will be vital if the private and public sectors are both to contribute towards increasing the exploitation of our national effort in science and technology.

Yours sincerely

Margaret Thatcher

Sir Henry Chilver

Contents

Foreword

On 25 October 1983, ACARD announced the establishment of a study of Promising Areas of Science. The objective of the study which was linked to the Council's role in advising Government on its Annual Review of Research (this review of the Government's total expenditure on R&D was announced in a White Paper, Cmnd 8591, in 1982), was to survey current scientific developments and advise the Council on work which showed commercial and economic promise in the medium to long term. A Study Group was set up with terms of reference outlined in the Introduction to this report.

The members of the Study Group were:

Dr C H Reece (Chairman)	Director of Research and Technology Imperial Chemical Industries plc
Mr A Best	Anthony Best Dynamics Ltd
Professor Sir Hermann Bondi FRS	Master of Churchill College, Cambridge
Mr R Cutting	Sinclair Research Ltd
Professor C Hilsum FRS	Chief Scientist, GEC Research Laboratories
Mr C S King CBE	Deputy Chairman, BL Technology Ltd
Professor J S Metcalfe	Department of Economics, Manchester University, and Director of PREST
Professor D K Peters	Department of Medicine, Royal Post-graduate Medical School
Professor Sir David Phillips FRS	Laboratory of Molecular Biophysics, University of Oxford
Professor G G Roberts FRS	Department of Applied Physics and Electronics, University of Durham, and Chief Scientist, Thorn EMI plc
Professor J M Thomas FRS	Department of Physical Chemistry, University of Cambridge

The Study Group held ten meetings over the course of the study and arranged a series of meetings with companies and organisations with major responsibilities for R&D. This report is based on the discussions of the Group and the views of those consulted during the exercise.

Executive summary

1. There is a thesis, widely accepted in the United Kingdom, that research cannot be organised to deliver economic return. The thesis is not generally accepted in other countries. They believe that science is now so important to a country's future that some attempt must be made to structure support, and achieve more effective exploitation of science.

2. This exercise is an overview gathered by the Study Group after consulting an incomplete but generally representative series of groups in the United Kingdom. It is therefore limited in depth and completeness. It is set against a backcloth study of the predictions of scientific futures in USA, Japan, France and Germany.

3. The report analyses the prospect for increasing the longer term economic return to the United Kingdom from it's expenditure on basic, strategic and industrial scientific research, and uniting their thrust so that it has an effective total impact.

4. We believe that the value of this report lies in its conclusion that a process is needed to prioritise and guide a substantial proportion of that part of the national scientific resource be it Research Councils, Ministry of Defence or, Department of Trade and Industry, and to stimulate its effective exploitation to the benefit of the United Kingdom. The remaining and significant proportion of publicly funded scientific research should be determined by peer judgement of scientific excellence etc in the established way.

5. The study recognises that past levels of support of UK science have been the desirable result of prosperity and that their fruits have tended to give benefits world-wide rather than to the United Kingdom. However, in the future, national economic success will be built on the foundations of scientific knowledge and capability. From this comes the challenge which we must meet — to use our considerable national investment in scientific ability for the national benefit, and at the same time significantly increase our exploitation of research and development done outside the UK.

6. We do not have a forum in the United Kingdom where we can manage the process referred to above. It is, we believe, a matter of national priority that such a forum be established.

Summary of the report

1. Countries with a major technological capability have developed mechanisms for holding debates about directions in science and technology and the associated policy. In this country, we do not have a forum in which to carry out this activity. In fact, we do not even have the information which would allow this to be managed effectively, and our presently dispersed data are essentially non-interactive.

2. The study we have carried out has led us to a view of the means by which the process could be pursued, given some trust and commitment by industry and the established scientific organisations. Such an activity cannot be done occasionally, but must be continuous, with sufficient resources committed, both in quantity and time, to ensure that there is consistency of judgement.

3. We conclude that it is both feasible and desirable to create a framework for an agreed process for generating strategic exploitable science priorities.

Outline of the Report

4. The study considered the economic and social activities in society and related them to their influence on technology in order to determine the science areas required to underpin that technology. Part I of the report is concerned with allocating resources to science and considers a process for generating more effective exploitation of UK science. In Part II we describe a case study of technology, science, and markets in communications and information, which represents a first approach to the problem of identifying exploitable areas of science. The first chapter outlines the origins of the exercise and sets out the terms of reference for the study which were:

a. to report on those areas of science and specific scientific developments likely to have significant economic consequences within ten years and within twenty years;

b. to comment, as far as possible, on the adequacy of the above areas of science in the UK in terms of the technology perceived to be required in the future.

There is a clear relationship between the study, the Annual Review of Government-funded R&D, and the Government's view on the Annual Review expressed in Cmnd 8591 that, 'skilful value judgements as to allocation of financial and manpower resources are, however, needed. This will involve distinguishing between vital and dormant areas, identifying gaps, disparities and duplications, and considering the opportunity cost of relinquishing certain areas of research'.

5. We consider in Chapter 2 the main issues which arise in the process of assigning promise to areas of science. We define an exploitable area of science as 'one in which the body of scientific understanding supports a generic (or enabling) area of technological knowledge; a body of knowledge out of which many specific products and processes may emerge in the future'. Thus the exercise is not perceived to be one of picking winners but of strategic policy aimed at creating a reservoir of knowledge out of which the, as yet unidentified, winning products and processes will emerge. An 'aide-memoire' for identifying promise in science is presented and some rules of thumb given for minimising the inherent risk in resource allocation that opportunities might be missed and promise extinguished.

6. The issues raised by such considerations are summarised in the form of a sequence of questions, each one focussing upon a particular aspect of exploitable science—

i. Which areas of generic technology are supported by a particular area of strategic science?

ii. Has the UK the scientific resources to advance a particular area of strategic research? If not, how quickly can resources be acquired eg by changing the emphasis of undergraduate and graduate programmes?

iii. Within a generic technology what classes of new products and processes will become possible within a ten or twenty year horizon?

iv. What indicators are there of the likely costs of translating knowledge from the generic pool into marketable products and processes?

v. In which areas of existing industrial and commercial activity will the new products and processes find initial application? What advantages will they offer and how might markets respond to these advantages?

vi. How quickly might the perceived markets develop and what might be the ultimate niches of the new products and processes?

vii. What evidence is there for a foreign industrial presence in the relevant areas and what implications does this have for UK market share?

7. The approach taken in the study is described in Chapter 3. Ways in which technological forecasting and scientific assessments have been made in the past both in the privately and publicly funded R&D domains are discussed. A brief outline is given of an exercise commissioned by the Study Group with the Science Policy Research Unit (SPRU) of Sussex University on how other countries undertake assessments of the potential of R&D.

8. In Chapter 4 we collect together our conclusions and recommendations. As indicated earlier we consider the exercise as only the start of a process requiring much more detailed analysis leading to implementation and resource allocating decisions. Our principal recommendation therefore is that *'a process should be established for identifying exploitable areas of science, which has some certainty of continuity, for the long-term economic health of the country'*.

9. In arriving at this conclusion we carried out a review of the current state of areas of science in the UK and their relationship with market need and technological opportunities. As our remit required, we looked at science from a traditional disciplinary focus and also across conventional boundaries. In Chapter 5 we identify technology as the bridge between science and markets, and draw attention to some general trends which will affect the future exploitation of science in the UK. Chapter 6 illustrates the approach taken with a preliminary case study of the information and communications sector. In this we identify major developments in science and technology which will shape the evolution of this sector.

PART I. ALLOCATING RESOURCES TO SCIENCE— THE NATURE OF THE PROBLEM

1. Introduction — allocating resources to science — the nature of the problem

1.1. *Background and Remit*

1.1.1. Central to the ACARD terms of reference is a charge 'to advise the Government and publish reports as necessary' on 'the application of research and technology, developed in the United Kingdom and elsewhere, for the benefit of both the public and private sectors in accordance with national economic needs'. The Council has published several reports on subjects relevant to this remit, for example, robotics, computer-aided techniques, advanced manufacturing methods. The object of those reports was to focus attention on new technologies in order to encourage their exploitation by industry.

1.1.2. A number of steps back from the point of exploitation of technology is a stage of scientific experimentation which increasingly forms the base from which new technologies and innovation flow; however, not all basic scientific research is exploited or exploitable. Historically, a prime motive of the scientific process has been the advancement of knowledge, but rarely does scientific progress occur without a point or points of reference; cross-fertilisation of ideas has been a rich source of scientific innovation in the past. Major scientific discovery is usually made in fields which have already been identified as having significant potential. In the fullness of time, many such discoveries lead on to new technologies. Such notions prompted the Council to consider the feasibility of identifying the fields of science on which future technology and innovation might be based. If such a process were feasible there would clearly be implications for technological development, industrial competitiveness and for resulting economic considerations. ACARD decided, therefore, with the endorsement of the Advisory Board for the Research Councils, to examine the feasibility of identifying areas of science which had significant economic potential for the future. At the same time, it was thought desirable to examine the adequacy of the national scientific research effort in relation to such scientific fields which were identified.

1.1.3. We were invited by ACARD, therefore, to form a Study Group with the following terms of reference—

a. to report on those areas of science and specific scientific developments likely to have significant economic consequences within ten years and within twenty years;

b. to comment, as far as possible, on the adequacy of the above areas of science in the UK in terms of the technology perceived to be required in the future.

1.2. *Scope of the Study*

1.2.1. In the spectrum of basic and applied science, there will be areas that informed observers will select as more likely than others to have economic potential on a ten or twenty year timescale. The exploitation of these areas may result in changes in industrial practice, the service sector, national infrastructure, health care, social conditions, the environment, lifestyles, educational techniques, etc. Perceptions of the areas which have economic potential will be formed from two fundamental considerations:

a. judgements on fields of scientific research which are likely to lead to new industrial and commercial opportunities;

b. judgements on the changes in society and the market-place which are likely to require the application of new technology.

1.2.2. Science comes in an infinite variety of shapes and sizes. The private sector often has a clear idea of where it thinks the research which it undertakes is leading in terms of the market-place. However, some private sector research and much public sector research is of a more speculative or curiosity-driven nature. The initial reasons for such research may be for advancement of knowledge but ultimately important technologies may arise. Development and commercial exploitation of such technologies will depend on a complex of factors but finally a market must have developed. Predictions about the potential of curiosity-driven activities implies some arbitrariness, but informed judgement at the time may in many cases have yielded a reasonable assessment of the likely potential of such research. *We considered the feasibility of such a process to be central to our remit.*

1.2.3. The scope of the study was confined therefore to those areas of science which we considered likely to be economically significant in the future, and included all the major fields, such as health, communications, energy, space, manufacture, defence, etc in which such areas might be located.

1.2.4. It is neither likely nor desirable that the *entire* budget for UK science should be treated in strategic terms. Many fundamental areas of research will remain, where the long-term interests of the UK are best served by leaving first-rate scientists to judge fruitful areas of research quite independently from external pressures. There are motivations for practising science other than the purely economic ones, eg for intellectual curiosity and for education and training. However, economic reasons cannot be ignored in the formulation of British science policy. It is a question of balance, and it is our judgement that economic and social factors have been given less weight in the formulation of science policy than is justified by Britain's economic circumstances.

1.3. *Annual Review of Government-funded R&D*

1.3.1. In June 1982, the House of Lords Select Committee on Science and Technology in its First Report made a number of recommendations about the organisation of Government advice on science. A major feature of the reply (Cmnd 8591) by Government to the report was the decision to introduce a system of Annual Reviews of Research. ACARD was invited by Government to comment on the issues raised in the Annual Review in order that independent advice could be obtained on the allocation of public expenditure resources to R&D.

1.3.2. The first review carried out in 1983 concentrated on assembling a database of Government R&D expenditures, and on establishing procedures for the collection of such information regularly in the future. It was not intended in the 1983 Review to set Government-funded R&D in any national or international framework. This was a major aim of the subsequent review. The 1984 Review emphasised that decisions on levels of R&D funding must be a matter of informed judgement based on knowledge of the prospective subject of study, taking into account other expenditure priorities. ACARD has provided its advice to Government on both reviews as an input to the process of such informed decision-making. The 1984 Review also commented that the analysis was a broad-brush exercise which could not fulfil all the objectives set out in Cmnd 8591 for the Review. It could only indicate areas where expenditures appeared to be out of line, whether with international figures or by comparison with their expected economic significance: further studies would be required. We see the study which we were invited to undertake very much in this context.

1.3.3. Cmnd 8591, in commenting on the Annual Review, concluded that 'the analysis required will not be a facile choice of areas where more money should be spent. In the Government's view, overall UK expenditure on research and development as a percentage of GDP is sufficient. Skilful value judgements as to allocation of financial and manpower resources are, however, needed. This will involve distinguishing between vital and dormant areas, identifying gaps, disparities and duplications, and considering the opportunity cost of relinquishing certain areas of research. The emphasis will be on review of long-term plans'. Clearly the study which we were asked to undertake by ACARD is highly relevant to the objectives outlined in Cmnd 8591. As indicated above, the Annual Review is well-established in terms of the basic information which it provides on allocations of Government R&D funding, and attention should now be focussed on scientific aspects of priorities for Government R&D funding.

1.4. *National Scientific Priorities*

1.4.1. The UK carries out roughly 5% of total world R&D, and cannot, therefore, be involved in all the areas of research which are covered by other countries. In the current range of national R&D activities a process of selection has taken place, however carried out, which has determined which areas were supported to the exclusion of others. It is the process of selection and the results of that process which is relevant to the second part of our terms of reference.

1.4.2. Concern has been expressed in recent years by those with interests in science policy that the processes by which national scientific priorities were determined were not clearly visible. There was no mechanism by which to assess the national competence in any particular technology or branch of science or to judge whether the process of selection paid sufficient regard to national needs in relation to factors other than those concerned mainly with excellence in scientific research.

1.4.3. At a national level, a need for clearer identification of priorities relevant to fundamental, strategic, and applied research has been expressed. It was concluded at a seminar in 1982 organised jointly by the Leverhulme Trust and the Society for Research into Higher Education that 'a national research policy is required to guide the allocation of public money to fundamental and strategic research'. The report of the seminar went on to suggest that priorities could not be left entirely to Government, and that 'there is a need in this country to find a mechanism which will allow the greater involvement in the determination of research priorities of higher education institutions, the UGC, the Research Councils, the scientific community and likely users of research — industry and Government'.

1.5. *International Aspects*

1.5.1. The nature of international competition and the cost of research are such that the development of new technology cannot realistically be treated in the context of a closed economy. Trade, foreign investment and licensing are alternative ways in which the returns to research may be garnered. Science in a historical context has rarely been hindered by international boundaries, and the scientific process has been benefitted from the close interaction of scientists in the world community.

1.5.2. To maintain its position within the world economy the UK will be required to draw deeply on its own resources of inventiveness and innovation. A thrusting higher educational research system is needed responsive to the demands to which it will be subjected. Countries which appear to have enjoyed success in scientific research and its application in recent years have made conscious efforts to formulate national research priorities for the basic sciences. The Japanese with their long-term plans and French with their national symposia on science have developed processes for identifying the scientific priorities, for influencing Government to make funds available for such priorities, and for obtaining a commitment to implementation of the priorities.

1.6. *Further Structure of the Report*

1.6.1. We noted at the outset of this exercise, as mentioned above, that those countries which had enjoyed most success in recent years in their exploitation of science had moved towards an approach or process for guiding national scientific and technological activities which was closely related to the ways in which their economies and societies were developing. In this report we discuss the relationship between such activities and support in strategic science and generic technology and industrial and commercial markets. This discussion is contained in Chapter 2. Ways in which different countries go about the process of relating scientific priorities to economic and societal factors were investigated by commissioning a study with consultants. The results of this study and the approach which we subsequently decided to adopt are outlined in Chapter 3. In Chapter 4 we conclude by giving our considerations and recommendations on a process for relating national priorities in strategic science to the needs of the economy and society.

2. Science, technology and economic performance in the UK

2.1.1. Our terms of reference in this exploratory study were to identify exploitable areas of scientific research, namely, areas where a basis for profitable commercialisation can be anticipated within a period of ten to twenty years. In this context, commercialisation means the transformation of scientific understanding into profitable new products and processes by UK firms. This chapter provides a brief overview of the issues which arise in the process of assigning promise to areas of science. We do not attempt to hide the complexity of the questions we discuss. Nor do we pretend to forecast future states of the world in more than the broadest terms.

2.1.2. In 1969, the Department of Education and Science published a report by the then Council for Scientific Policy (CSP) entitled 'An Attempt to Quantify the Economic Benefits of Scientific Research'. That report pointed to the close association between applied research and its economic justification, and noted that although fundamental scientific research was carried out for its cultural value and intellectual challenge, it had often given rise also to unexpected technological progress. Suggestions were made on how the economic benefits of science might be assessed, and the need to make an appraisal of underlying scientific discoveries in relation to their economic significance for the industries on which they had been based. The aim of such assessments was to make possible the prediction of long-term economic changes resulting from support of particular scientific areas.

2.1.3. At the time, the report was particularly forward-looking. Thus, although the CSP Report proposed a series of *ex post* studies of science-based industries which were to be confined somewhat narrowly to the underlying science, the report also recognised that it might be necessary eventually to consider the interrelations between all science-based industries and all associated scientific discoveries. It was realised that such a task would not be straightforward, even with the assistance of techniques such as systems analysis and critical path analysis. Furthermore the report also acknowledged, more in passing, that in such *ex post* rationalisations, it might be difficult to distinguish features of society resulting from previous scientific activity from changes due to other organisational/market forces in society, or to determine the extent to which such changes were related to previous technical/scientific advances. Nevertheless, it was considered, in full recognition of the magnitude of the problem, that it would be worthwhile to explore these ideas further, and the CSP set up a Working Party to consider possible methods of quantifying the economic benefits of scientific research. Before the Working Party had reported, however, the CSP became defunct in 1972.

2.1.4. Since that time interest in such studies, and assessments have been pursued in other forums both nationally and internationally. Both academia and industry have sought to develop and analyse information on scientific and technological activities and relate these to technical innovation and development in order to improve the basis for policy and theory. In such analyses there is a clear difference in approach to the science carried out in the private sector to that carried out in the public sector. Although scientific assessments in both sectors rely to some extent on extrapolations of past trends, the assessment by industry of the technological potential of applied research relies on a more structured approach, incorporating economic, technological, socio-political and other parameters, than does assessment of public sector science. Assessment of public sector research tends to be inherently more difficult than that of private sector research because the objectives are less clearly defined in the economic sense and it is less process- or product-orientated.

2.2. *Scientific Support and UK Economic Performance*

2.2.1. The Government believes that the resources available for scientific research should depend primarily upon the level of gross domestic product, so that any substantial increase in resources for science in the United Kingdom is most likely in the longer-run to be funded by economic growth. The economic performance of the UK economy since 1945 has been so weak compared to that of other countries in the OECD to raise doubts about the capacity of the UK to support the scientific community at previous levels. For example, the support per scientist in the UK has, in the past, been greater than in most European countries and fell little behind that in the USA. But it is likely to become lower compared with both in the future, which will be of importance because of the competitive nature of science. The relatively poor performance of the UK economy is reflected not only in the statistics of *per capita* income growth but also in the statistics of foreign trade, with the UK share of world exports of manufactures falling from 20% in 1954 to less than 9% in 1984. In world terms the UK is a small economy with its standard of living heavily dependent upon foreign trade. The trade pattern is no longer one of exporting manufactures to less developed and Commonwealth countries in exchange for imports of food and raw materials. Rather it is dominated by trade in manufactures and semi-manufactures with the advanced industrial countries of Western Europe, North America and Japan. In 1984, over 75% of UK imports and 66% of UK exports involved trade in highly competitive markets for manufactured and semi-manufactured goods compared with figures of 53% and 79% in 1955. So far as services such as banking, insurance, consultancies, etc are concerned, the export ratio was 23.5% in 1983 compared with 27% in 1962 and the import ratio 18.5% as against 23% in 1962.

2.2.2. The exploitation of North Sea oil resources has had a profound effect on the UK economic structure. The higher real exchange rate which has resulted is an important factor in 'crowding out' UK manufactured exports and generating in 1983 a negative trade balance on manufactured goods for the first time since records began. Yet North Sea oil will be exhausted some time, be it in 20, 50, or 100 years, and the consequent reduction in income will require the development of new export opportunities if UK standards of living are to be maintained, let alone grow at average European rates.

2.2.3. It is here that a policy for strategic science becomes particularly significant. The export opportunities which maintain standards of living are those which offer high value added per unit of employment; products with a knowledge base in advanced technology which can be sold on world markets at favourable terms of trade. The products of relatively mature technologies are increasingly the preserve of low-wage newly industrializing countries with which the UK has little realistic prospect of competing without a drastic fall in living standards.

2.2.4. Japan, for example, has experienced very rapid import penetration from less developed countries in a number of mature technological areas, and has yet maintained the most impressive growth rate in the industrial world. The reason lies in the close link between structural changes and economic progress as new dynamic industries expand and displace existing activities. In the general process of growth the agricultural sector declines relative to manufacturing, which in turn is eclipsed by the growth of the service sector, while within the manufacturing and service sectors new activities continually emerge to compete with and displace established activities. No single technology offers unlimited scope for improvement so the process of growth has to be sustained by new economic impulses based upon innovation, that is, upon an entrepreneurial injection of new technological activities into the economy.

2.2.5. The role of strategic science policy over the next twenty years of UK economic growth then becomes clear. On the one hand, it should contribute to existing activities keeping close to world best practice. On the other hand, it should respond to the important export and growth opportunities which lie in newly emerging technologies where the knowledge base is changing rapidly enough to prevent low-wage countries establishing a technological presence. To grasp opportunities at the cutting edge of international competition will require new patterns of resource allocation, and the allocation of resources to strategic science should be seen as an integral part of this market driven process. Structural change is, of course, painful in the short-term as particular skills are no longer needed and regional concentrations of industry decline. But, over the longer-term, a failure to develop new economic activities has even more painful consequences for the nation as a whole. *Of itself, strategic support of science is a small but necessary part of this picture of growth and transformation.*

2.3. *The Nature of Exploitable Science*

2.3.1. An exploitable area of science is one in which the body of scientific understanding supports a generic (or enabling) area of technological knowledge; a body of knowledge from which many specific products and processes may emerge in the future. It is this connection with future technological development which gives the exploitable area strategic importance. Thus exploitable areas of science exist 'where the basic principles are known but the final products have yet to be identified' (Improving Research Links between Higher Education and Industry, ACARD/ABRC, 1983, p.11). It is intrinsic to this definition that exploitability depends upon three sets of considerations:

i. the potential for development within the area of science;

ii. the generic technologies which will be advanced by a greater understanding of the particular fundamental scientific principles; and

iii. the potential areas of application which products and processes flowing from the generic technology will have.

2.3.2. According to Frascati definitions of R&D, basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application in view. So far as the Annual Review of Government-funded R&D is concerned, it was recognised that basic research was often considered by the funding agency to have a strategic dimension, and that the division between basic and strategic aspects of such research was difficult to identify. For applied R&D, it was possible for the customer to distinguish and quantify the precise practical aims and objectives of the programmes. Applied research with strategic aims was, therefore, research directed primarily towards practical aims or objectives, but it was too early in the evolutionary cycle of the subject under investigation for the eventual applications to have been clearly specified. The actual duration of the strategic phase of the evolution of a field of study would vary widely from field to field.

2.3.3. The identification of promise will require a blend of judgements involving questions both internal to and external to the pursuit of fundamental science. The matching of extrinsic and intrinsic criteria in the pursuit of national objectives will, in turn, require an institutional and decision-making structure which does not locate strategic science and industry in different, mutually exclusive categories. Rather it will require a framework which draws together the relevant knowledge inputs, establishes communication between science and industry, mobilizes resources in pursuit of the strategic objectives, and changes the balance of support as the potentials of market exploitation, scientific advance and technological development evolve. Flexibility in response to changing priorities will be a central element in any policy of strategic support for science. Government programmes with emphasis on pre-competitive research involving collaboration between university departments and industry are one measure which may find wider application in a policy of strategic support.

2.3.4. It will be clear that technological knowledge bridges the gap between strategic science and the market-place. The likely success of a programme of strategic scientific support will depend not on treating the development of the scientific and technological knowledge as independent, sequential stages but rather in treating them as interdependent processes, advancing in step in the development of a generic pool of technological knowledge. To seek to organise science in such a way that it leads naturally to exploited technology is the objective. Strategic science is a national investment to be justified in terms of the national return it promises to generate. The organisation of strategic science should, therefore, reflect this need for results to be followed by exploitation in the national interest. Effective interaction between industry and the scientific community is vital if strategic research is to succeed.

2.3.5. It would be foolhardy in the extreme to pretend that the identification of exploitable areas and their commercialisation is straightforward. Picking precise winners is not a feasible policy option. The process by which new industrial activity is generated and absorbed into the prevailing economic structure is one of immense complexity. Nevertheless, it is clear that technological innovation has been and will continue to be the mainspring of economic growth and, moreover, that future technological development will depend closely upon advances in scientific understanding.

2.3.6. To forecast exploitable areas in any precise way is no less difficult, the links in the chain are many, the uncertainties at each stage considerable, while the possibilities of success or failure also depend upon decisions made in the many countries which compete with the UK in world markets. Nonetheless, we believe it is possible to identify broad areas of activity where a change in scientific knowledge or of market trends will make it profitable for industry to develop new products and processes.

2.3.7. Rather than pick winners in this narrow sense, strategic policy is concerned to create a reservoir of knowledge out of which the, as yet unidentified, winning products and processes will emerge.

2.3.8. The case for public support of strategic science lies in its having long-term implications without as yet offering a return to immediate exploitation in the market-place. Thus strategic science falls in the gap between fundamental science and applied science, being neither the primary concern of the university sector nor of private industry. The time horizons, attitudes to risk, and objectives which motivate scientific research in the two sectors are sufficiently different to provide little incentive for strategic research to be performed by either. Much of the work supported by the Research Councils is, however, strategic. Like basic research, strategic research is concerned with advancing fundamental knowledge, and like applied research it is concerned with developing new technological possibilities. It is at this interface when different attitudes to risk and different objectives meet, that the problems of identifying and funding strategic research arise.

2.4. *Selectivity and Strategic Support*

2.4.1. The resources available for scientific research are always limited relative to the claims which can be made on them. Science policy cannot avoid questions of choice, the setting of priorities, the sacrificing of some areas of science in favour of others. Naturally this entails risks but this is true for any realistic situation in which limited resources have to be allocated.

2.4.2. In this context a policy for selecting exploitable areas of science explicitly must introduce criteria for choice which are external to science. Within the Research Council system both external criteria and criteria of intrinsic scientific worth are taken into account, particularly in those Research Councils—AFRC, MRC and NERC—whose remits are essentially focussed on practical problems. However, while external criteria are clearly taken into account within the Research Council system, neither the individual Councils nor the ABRC have comprehensive information about externalities—scientific, technological, economic and social developments; nor do they have mechanisms for systematically presenting and evaluating this information. Neither is there a system to determine the relevance of commissioned research which is wholly aimed to produce benefits as perceived by Government departments.

2.4.3. In allocating funds for strategic reasons internal scientific judgements remain indispensable but are no longer sufficient, and have to be supplemented by judgements of commercial and technological relevance, that is, by judgements of the external worth of the particular scientific area. In general terms these external judgements relate to two situations:

i. where the products and processes which ultimately stem from the strategic science will be valued in the market-place;

ii. where a need is apparent but the commercial criteria are not applicable, either because relevant markets are non-existent, or give distorted signals to decision-makers. The science and technology related to environmental protection, health and defence are important examples within this category.

2.4.4. The definition of the margin between strategic and non-strategic work will be an important element in a policy to support exploitable areas of science. Considerations of strategic research cannot avoid comparison with fundamental research as well, since the use of external criteria implies judging the competing demands of strategic and fundamental research for the same resource.

2.5. *Investment Decisions and Exploiting Science*

2.5.1. The support of exploitable areas of science can properly be viewed as an investment decision, in which current outlays are incurred in anticipation of future returns. The objective would be to create a portfolio of areas of science on which UK industry would draw over an extended period, to ensure its future competitiveness in international markets as outlined in the 1983 joint ACARD/ABRC report 'Improving Research Links between Higher Education and Industry', referred to earlier.

2.5.2. The elements of a strategy are criteria for choice, the identification and collection of relevant information, and an institutional mechanism which ensures that UK industry does indeed draw successfully on the strategic sciences and related enabling technologies. A policy which succeeds in generating good, commercially relevant knowledge will have failed if UK firms do not exploit the related technological opportunities. It will have failed *a fortiori* if that knowledge base is exploited by overseas competitors. The matching of knowledge and exploitation in the UK is the key objective in any policy of strategic science. A successful strategy will require that a process is established with clear elements of continuity to achieve this objective.

2.5.3. The choices to be made in allocating funds to strategic research fall into two related categories: the areas of science to be given strategic status; and, the levels at which those selected are to be funded. If one area is selected as exploitable, the level of support should reflect the date in the future at which profitable commercialisation of the related technologies is expected. The funding policy should provide the resources to ensure that all relevant knowledge is acquired by the expected date of commercialisation. That the timing element is important in exploitable research is not surprising. Modern industrial history is replete with examples of misplaced technological endeavour in which either the UK was too late — allowing competitors to build a commanding commercial advantage — or too early — investing in a technology before market opportunities had emerged. The greatest increase in national wealth is obtained not simply by developing new technologies but by developing them at the right time. The ability of UK firms to exploit promising science is not independent of the strategy of foreign competitors or their effectiveness in development and exploitation. Of course, the fact that any area of science is not of strategic importance at the present moment in no way rules out its becoming strategic at a future date. Successful policy will have to accommodate shifts in priorities over time and be flexible enough to effect these changes.

2.5.4. The usefulness of any investment framework lies in the insights which arise from its systematic application. By providing a framework for informed choice, it identifies the information which is required, even if in practice that information can be based on no more than intelligent guesswork.

2.5.5. Broadly speaking, the framework identifies costs and benefits associated with the support of strategic research. The relevant costs relate to the programme of research funding over a period of years, while the benefits relate to the commercial and other consequences of exploitation *net* of the costs of translating the generic pool of knowledge into specific products and processes. Whereas the support of exploitable areas of research will be met by public funding, the costs of developing specific products and processes will fall to a greater degree upon UK industry. The balance of funding between public and private support will require careful consideration to ensure that promise in science is translated into exploitation in the market-place.

2.6. *The Costs of Strategic Research*

2.6.1. The costs of strategic research depend on the capital intensity of the research process, the quality of the research teams, and the level of fundamental understanding which exists in the research area. Since the outcome of a research programme is surrounded by uncertainty, some judgement has to be made as to the bounds of possibility, and the 'real costs' adjusted accordingly. Also, it is more difficult in some areas than in others to change course in response to new opportunities because of long lead times in equipment and skills, and this is often an important factor in making choices.

2.6.2. All other considerations being equal, the case for giving an area strategic support becomes stronger the lower is the anticipated cost of acquiring the relevant knowledge.

2.6.3. The nature of international competition and the cost of research are such that the development of new technology cannot realistically be treated in the context of a closed economy. Trade, foreign investment and licensing are alternative ways in which the returns to research may be garnered. Science in an historical context has rarely been hindered by international boundaries, and the scientific process has benefitted from the close interaction of scientists in the world community. Indeed, the fact that the results of scientific research are disseminated internationally implies that the UK can supplement its own strategic programmes by drawing upon the results of foreign research. It is frequently observed that foreign technological programmes successfully exploit the results of UK research and there is no *a priori* reason why the converse should not hold.

2.6.4. It is unlikely, however, that this will be possible unless the UK maintains at least a gatekeeper presence in a given area, with a sufficient investment in manpower and facilities to replicate and improve on foreign advances as and when they occur. Below this threshold, which will vary across sub-disciplines of science, the UK could not hope to gain direct access to the best practice strategic science developed overseas.

2.6.5. International collaboration may also be possible in some circumstances, provided that the countries concerned can agree on strategic objectives. The degree to which UK strategic science can be based upon international collaboration will depend on the extent to which exploitable areas have been identified world-wide, and the extent to which UK policy seeks to develop areas independently from major competitors. Pre-competitive joint ventures between UK companies and between UK and foreign companies may also offer advantages in the development of specific products and processes arising from the generic pool of knowledge. This may be particularly relevant where UK companies are small relative to Japanese, American and European competitors. The recently announced EUREKA programme within Europe provides one example of possible collaborative arrangements.

2.6.6. To maintain its position within the world economy the UK will be required to draw deeply on its own resources of inventiveness and innovation. A thrusting and more entrepreneurial higher educational research system is needed responsive to the demands to which it will be subjected. Countries which appear to have enjoyed success in scientific research and its application in recent years have made conscious efforts to formulate national research priorities for the basic sciences. The Japanese with their long-term plans and French with national symposia on science have developed processes for identifying the scientific priorities, and for obtaining a commitment to implementation of the priorities.

2.7. *Benefits from Exploitable Science*

2.7.1. The benefits flowing from a programme of exploitable science depend ultimately upon the products and processes which UK industry develops and exploits in world markets. *Elements of entrepreneurship are an indispensable component of a successful strategic policy.* The benefits will in each case depend on the improvement in performance that the new products and processes offer to their users, either in terms of cost reduction or enhanced capabilities. The greater the advantages which the new technologies provide, the greater will be their ultimate application, and the more quickly they will be absorbed into the economic structure. The pace of absorption is of considerable importance in determining the economic return to innovation. The application of new technology always involves the displacement of existing productive activities and there are natural barriers to this substitution process, partly economic, partly social, and partly relating to the inherent uncertainty surrounding the characteristics of new technology. The more quickly markets absorb the new technology, the greater the wealth generated, and the greater the justification for supporting the underpinning areas of strategic science. One need only to note the power of compound interest to see the importance of timing. At a rate of interest of 10% (a modest one for risk-laden ventures) a sum of £1,000 today would have an equivalent present value of £390 in ten years time and only £150 in twenty years time. All other things being equal, the case for strategic support is greater the greater the range of application of the new technology and the quicker the economic application is likely to occur.

2.8. *Niche Concept*

2.8.1. An ecological analogy is sometimes helpful. When treating the question of competition between different species, ecologists employ the concept of a niche to reflect the interaction between environment and the rival species. Exploitable areas will give rise to new technological species introduced into a commercial habitat, populated with existing industrial activities, and the problem is to identify the niche and the costs of filling it with profitable UK-based activity.

2.8.2. Consider, for example, developments in opto-electronics. The technology flowing from this could affect a wide variety of information-disseminating activities. The opto-electronics niche could be identified with regard to:

a. a range of existing information-disseminating activities which could be directly affected. Telephone, telex, newspaper, and library activities come immediately to mind, as do cable television and possible niches in medical electronics and control engineering;

b. alternative technologies which compete for a niche, eg cable versus satellite-based communications.

2.8.3. The extent to which the potential market benefits may be captured by overseas competitors must also be part of the assessment procedure. From a narrow viewpoint the UK, *qua consumer*, can always obtain the benefits of new technology by importing the relevant products. However, in so doing, it forfeits the incomes which could be earned in their production and thus limits the general capacity to consume and benefit from the new technology. Considerations of international competition impinge upon the selection of exploitable areas in a number of ways. The ability of UK firms to exploit overseas markets enhances the return to UK from strategic science. Evidence of foreign scientific activity provides a case for accelerating UK efforts, in order to prevent competitors developing a lead time which renders UK production unprofitable. Conversely, in areas where UK industry does not have an anticipated competitive edge, the case for a strategic research underpinning of these technologies is correspondingly reduced.

2.9. *Net Benefits*

2.9.1. In assessing the benefits expected from a programme of strategic science, account must be taken of the very high development costs likely to be incurred in translating the pool of generic knowledge into specific products and processes. Such costs must be subtracted from the identified commercial returns to arrive at a net benefit figure. These downstream activities have rightly been identified as major overhead costs — incurred in development, design, construction of pilot plant, and other activities to capitalize on generic knowledge. To spread these overheads requires a large market, and for the UK this can often be achieved only in international terms, by entering markets within the advanced OECD countries of Europe and North America.

2.9.2. To minimise the costs of exploiting the generic pool of knowledge it will be necessary to establish continuous close collaboration between industry and the scientific community: to ensure that research objectives and resource commitments illuminate the problems found in particular areas of technological development. The Alvey programme may provide a good guide in this respect.

2.10. *Identifying Exploitability: Aide-Memoire*

2.10.1. The issues raised so far may be summarised in terms of a sequence of questions, each one focussing upon a particular aspect of exploitable science.

i. Which areas of generic technology are supported by a particular area of strategic science?

ii. Has the UK the scientific resources to advance a particular area of strategic research? If not, how quickly can resources be acquired, eg by changing the emphasis of undergraduate and graduate programmes?

iii. Within a generic technology what classes of new products and processes will become possible within a 20 year horizon?

iv. What indicators are there of the likely costs of translating knowledge into marketable products and processes?

v. In which areas of existing industrial and commercial activity will the new products and processes find initial application? What advantages will they offer and how might markets respond to these advantages?

vi. How quickly might the perceived markets develop and what might be the ultimate market niches of the new products and processes?

vii. What evidence is there of a foreign industrial presence in the relevant areas and what implications does this have for UK market share?

2.10.2. It is inevitable that hindsight will indicate opportunities missed and promise extinguished but such risks are inherent in any process of resource allocation in which relevant information is scarce. They should, however, be minimised by adopting rules of thumb of the following simple kind:

i. Support a portfolio of strategic areas with individual prospects for exploitation which are positively correlated or at worst independent;

ii. Select strategic areas where the generic technologies suggest a wide field of industrial and commercial application;

iii. Continuously monitor science and technology programmes in major international competitors;

iv. Establish close liaison between the scientific, industrial and financial communities in the UK to facilitate the free flow of information on exploitable science and the establishment of a shared vision;

v. Terminate programmes where the case for them is no longer supported by criteria of strategic promise.

2.10.3. Precise answers to these questions will never be available for today's decision-makers, they will only be revealed as the new products and processes are absorbed into the economic structure. However, intelligent guesses can be made and these should provide an initial guide to areas of promising science. Strategic decisions should not be seen as irrevocable. A policy for exploitable science is a process, in which decisions are made in the light of the best available information and reviewed as and when new information becomes available.

3. Approaches to foresight activity in strategic science

3.1.1. We discuss briefly in this chapter some approaches to assessing the potential for emerging areas of science in both the public and private sectors. Also described is a survey which we commissioned with the Science Policy Research Unit, Sussex University, to investigate how some other major industrialised countries went about the process of generating a view on scientific priorities. Finally we outline our approach to developing an overview of exploitable science.

3.2. *Technological Foresight in Industry*

3.2.1. Technological forecasting is an aspect of long-term market forecasting, which became of widespread interest to many major companies in the mid-1970s. Various techniques were developed each somewhat similar to the other, with the basic objective of assisting in the decision-making process on R&D and innovation. A typical approach was to assemble a high level corporate team or engage a firm of consultants to examine future technological trends and the related market potentials, the reasons for such trends, the way in which they might impact on company business, and how the company should respond to the opportunities presented. For many companies the results of such types of forecasting proved to be disappointing, perhaps because many forecasts were merely extrapolations at a time of high economic growth and they identified little that was not already known, whereas the economic changes in the last decade have produced many discontinuities which had not been foreseen. The lessons from such exercises indicated that forecasting was more successful when

a. the innovation process was clearly understood ie technology 'push' and market 'pull' were both essential in company research and innovation;

b. close collaboration was required between those undertaking the forecast whether inside or outside the company and research workers and management within the company;

c. a receptive attitude to the forecast was required at senior management level in the company.

Forecasts also tended to be more satisfactory in relation to a narrow range of technology than when consideration of a broad range of technologies was required.

3.2.2. In reaction to the relative lack of success, the credibility in the techniques used has been reduced; nevertheless, organisations require a view of the future in order to develop strategies which enable them to adopt rapidly in a period of fast-moving economic and scientific changes. Such a view can only be obtained by using the most reliable source of data and developing insights in a systematic and structured fashion. The technologist involved in innovative development often underestimates the effort required to complete development of the innovation, and often has inadequate perception of changes in market or technological conditions which might affect exploitation of the innovation. The success of innovation is dependent on the relationship between technological potential, and future market need. Completely accurate forecasting is not possible, but such precision is not essential anyway for many long-term planning purposes. The error in forecasting should not be a major determinant of the success or failure of an innovation. But forecasting can be a valuable tool to assist in decisions to identify innovations likely to be a major success and to avoid major failures. Perhaps the greatest value in such forecasting activities is the development of comprehensive databases and the increase in confidence which their use gives in planning future directions. Such decisions are concerned essentially with human behaviour and as we discuss later in relation to technological assessment in Japan, forecasting is closely related to the behavioural aspects of decision-taking.

3.3. *Scientific Foresight in Publicly Funded R&D*

3.3.1. Technological forecasting holds greater potential, in spite of the aforementioned difficulties, for strategic or applied research than for basic or curiosity-orientated research. But the increasing complexity of organisation and management of publicly funded R&D, against a background of rapid economic and scientific change, has highlighted the need to develop procedures not only for recognising the important areas of curiosity-orientated science *per se* but also for identifying the areas of such research with significant strategic potential, in order to establish priorities for support of these areas.

3.3.2. The apparent absence of an underlying rationale for support of basic science was noted some 20 years ago. Two sets of criteria were suggested for determining the relative assessment of support for different scientific activities. The first related to internal criteria relevant to the advancement of scientific knowledge and the second, to external criteria, related the wider effects which science might have on other scientific fields and to society, for example, in the form of new ideas and techniques for industrial exploitation. In general, internal regulation has been the primary mechanism by which basic science has been organised and the distribution of resources within fields and specialities controlled. The system used for such regulation has generally been termed peer-review. Up to the mid-1970s when support for scientific research was increasing rapidly, such a system worked reasonably efficiently in ensuring that most science of merit was supported. However, the slow-down in growth of science budgets has placed pressures on the system, and attention has been drawn by Irvine and Martin to three problems which such pressures have produced

a. the resources which big sciences consume are disproportionate to the total scientific activity which big sciences generate;

b. the concentration of research activity within fewer institutions which has tended to reduce their accessibility to the wider scientific community;

c. the peer-review system had become less appropriate as a mechanism for restructuring scientific activity.

Another problem relates to the unsatisfactory nature of peer-evaluation in identifying declining science areas and groups, because of the deep-rooted institutional and social factors which would require to be addressed.

3.3.3. Although external criteria have played a part in determining the overall levels of support for science and to some extent its distribution, such criteria have tended to reflect the needs of the scientific community along the lines described above. However, recent resource constraints have increased the pressure on the scientific community to have greater regard to external criteria in order that basic research results in more tangible and practical benefits for society. Of particular concern is the need to establish procedures for determining priorities between fields. The present distribution possibly reflects more post-war scientific planning decisions than a conscious effort in subsequent years to establish priorities on a systematic basis defined by present or future national needs. The availability of improved statistics through, for example, the Annual Review of Government-funded R&D, and work of bodies such as the Advisory Board for the Research Councils, University Grants Committee, National Advisory Board, etc will assist in providing a clearer picture of R&D support and facilitate a more directed approach to the organisation and management of publicly funded R&D.

3.4. *Other Foresight Activities*

3.4.1. *Science and Engineering Research Council*

The SERC's main concern has traditionally been to sustain the universities' research capability across the range of academic scientific disciplines where the allocation of funds has been based primarily on criteria of intrinsic scientific worth. However, over the last 10 years SERC has built up its engineering programmes under the direction of its Engineering Board—on which industry is strongly represented and where questions of industrial relevance are taken into account in the allocation of funds. With DTI, SERC has also developed collaborative programmes with industry in both engineering and science. Prospective industrial applications are increasingly taken into account by SERC's Science Board.

In September 1984, the Science and Engineering Research Council (SERC), published a report entitled 'A Strategy for the Support of Core Science' which represented the SERC Science Board strategy for defining and developing the research themes crucial in underpinning the science-base sectors of the national economy and for which a strong core science capability was required. In developing their strategy, the Board emphasised the importance of multidisciplinary activities and proposed that SERC central facilities could perform an important function in promoting multi-disciplinary studies. Difficulties imposed by the compartmentalised funding of research were recognised.

3.4.2. We applaud this initiative by the Council particularly the recognition that a continually evolving strategy is required incorporating not only considerations of scientific merit, but which also has some regard to the needs of the science base of industry, and urge that universities will take due action in formulating their academic plans for the next 10 years.

3.4.3. *Royal Society Study of the Health of the Science Base*

At the invitation of the Advisory Board for the Research Councils, the Royal Society embarked on a study in 1984 of the health of basic science in Britain. The exercise will concentrate on two broad areas of basic research of far-reaching scientific, and, ultimately economic importance. By looking at trends over the last 20 years, an attempt will be made in the study to assess the health of basic science in the two areas in absolute terms and by comparison with the performance of other countries. Resources made available for basic research (inputs) and the products of basic research (outputs) will be examined.

3.4.4. *Study by the Science Policy Research Unit*

Before embarking on the task set in our remit by ACARD we considered it necessary to make some enquiries initially on how organisations in other countries went about the business of identifying emerging areas of science which at the time showed potential for significant economic development in the future. We therefore invited the Science Policy Research

Unit (SPRU) of Sussex University to undertake a study to review previous appraisals of scientific developments that showed long-term (10 years or more) promise of commercial exploitation. The principal objective of the study was to report on:

i. assessments, which had been carried out in the last 20 years, of scientific developments that showed promise at the time of the assessment of leading to technological developments of economic significance;

ii. the role which the assessments might or might not have played in such developments;

iii. retrospective studies of significant technological developments to trace the science on which they were founded and determine whether any predictions could have been made of the economic significance of the basic science;

iv. the techniques that might be employed in a study of exploitable areas of science undertaken under the auspices of ACARD.

3.4.5. The study covered four major industrialised nations, namely, the United States, Japan, France and West Germany. We have not included the full report of the SPRU survey. The findings were reported in a book published in November 1984.

3.4.6. The main conclusion was that 'the United Kingdom should attempt to bring the level of its long-term scientific and technological foresight activities up to that found in Japan'. The 'desirability of integrating, as the Japanese have done, the forecasting efforts of Government funding agencies, and industry, something which can only be achieved by drawing in wide sections of the research community' was also emphasised.

3.5. *Our Approach to the Identification of Exploitable Science*

3.5.1. The SPRU study indicated, that of the four countries studied, Japan had a more committed approach to forecasting than had the other countries and detailed scientific assessments had become accepted as an essential component of national and industrial R&D strategy. Also, Japan tended to make longer-term projections than did other countries. The approach proposed in the SPRU study contained many features to which we were attracted but we felt that it was not completely appropriate for the circumstances which existed in the United Kingdom. We considered that the inherent differences between the two countries in R&D organisation and management were sufficiently great as to require some modifications to the proposals made by SPRU for the purpose of this study. For example, the proportion of research carried out by the private sector is much higher in Japan than in the UK, and the recent recessionary trends had less impact on Japanese industry. The research base in the UK is spread across a wider range of organisations each with varying objectives. Perhaps our clearest impression from the SPRU findings in Japan is that the Japanese showed almost a total dedication to the forecasting process, irrespective of the quality of the outcome and by such commitment made them almost self-fulfilling.

3.5.2. We believe, therefore, that it is possible to develop an assessment of scientific areas with potential in the UK using the approach outlined below but in order to obtain a commitment on the Japanese scale, changes in attitudes are required which largely depend on three factors:

i. a longer-term view of scientific innovation;

ii. co-operation and communication of information between competing commercial interests, higher education institutes and Government;

iii. acceptance of the consequences of major structural change.

3.5.3. Our views on the reason for Japanese success in technological forecasting are confirmed by a 1983 report on 'A Case Study of Technology Forecasting in Japan' by Professor Dore of the Technical Change Centre. The report describes the highly effective process by which priorities were set in the choice of scientific projects in relation to the balance between technological potentiality and market prospects, but the success in achievement was based on a complete commitment by a 'a consensus society' to the choices made.

3.5.4. We were attracted by the suggestion of circulating a questionnaire to the R&D community but were not persuaded to pursue this approach since it was uncertain whether the replies would contain the information necessary for a comprehensive assessment to be made. The approach which we decided to adopt therefore was to seek a range of opinions on areas of science with economic potential from scientific workers at the laboratory bench to leaders in the scientific community and corporate planners in industry. Information was also sought on social change, market and resource trends, overseas developments in science and technology, political, economic and trade considerations.

3.5.5. In order to obtain a broad spectrum of scientific and other views links were established with a wide range of knowledgeable people within the scientific and technological communities. Major forward-looking UK manufacturing companies and other organisations were approached in order to gain an insight into their thinking on the science which would present future opportunities and markets. Another perspective on the potential of science was also obtained through approaches to major science and technology institutions like the Royal Society, Fellowship of Engineering, and Research Councils. (A list of the organisations visited is included at the end of the report.) Each organisation approached was invited to form a small group consisting of, for example, an outstanding laboratory scientist, design engineer, research team leader, technical director, forward planner, economic forecaster, etc. In the case of the science and technology institutions the groups consisted of outstanding young scientists/engineers and scientists/engineers eminent in their particular field of interest. Arrangements were made for a pair of members of the Study Group to visit each organisation to hold a free-ranging and uninhibited discussion on scientific areas likely to have significant economic consequences. Such discussions took place over half a day or, occasionally, a full day. At the outset of each meeting it was stressed that information given would be treated confidentially. A report on each meeting was produced and forwarded to the organisation for their comment/amendment or further elaboration. This process of consultation has involved a considerable body of people and allowed collection of information at a level of detail which might not have been possible by circulation of a questionnaire.

3.5.6. We would not wish to give the impression that the consultation meetings were completely unstructured. Careful consideration was given to the approach to take in the discussions and a framework of questions was drawn up to ensure that the major interests of the study were covered, and that themes were broadly similar from meeting to meeting so that comparisons could be made. The major theme questions were as follows:

a. What do you consider to be the most important areas of science likely to realise future economic returns within a 10 year and a 20 year time-scale?

b. In the case of industrial companies,

   i. Can the main technologies likely to be used in your industry in the next decade and possibly the following decade be identified?

   ii. What are the newly emerging technologies in your sector?

   iii. What technical progress do you consider necessary in supporting sectors and is the rate of progress adequate?

c. Does the nation allocate its resources for scientific research properly, and can you identify unimportant areas of science receiving too much support and important areas receiving too little support?

d. How do you consider changes in markets and society will affect the directions of science undertaken by the country?

e. What are the methods employed for corporate planning of future research and development activities, and how and where do you get the data or information on the technical factors, markets, etc which you take into account when formulating long-term strategy?

f. Would a UK strategic overview of science be of help and made use of by your organisation in planning for the future and if so would you be willing to share that commitment with competing UK organisations against foreign competition?

A supplementary list of questions was also available for use in following up lines of enquiry. Not all questions were relevant to some organisations and in practice a flexible approach was taken in using the framework of questions during discussions.

3.5.7. In order to obtain information an area of science with potential being developed in other parts of the world, approaches were made to the Scientific Counsellors in major industrialised countries seeking their assistance in providing information on the scientific technical-commercial scene world-wide so as to identify exploitable new scientifically-based developments which offered potential market applications in the various industrial sectors. The sources for such information included overseas companies, national statistics, universities, scientific conferences, symposia, technical literature, data on market sizes/growth rates, competitive situation, etc.

3.5.8. We also collected a wide range of published material on contemporary science in the research literature, Government statistics and data on R&D, research plans of organisations, and relevant consultants' studies.

3.5.9. Our views on the process of identifying exploitable science have been greatly shaped by the consultative approach described above.

4. A process of exploitable science

4.1.1. We assembled a considerable body of information on science areas during the course of the study which has been used to draw together in this chapter our conclusions and recommendations on the process by which exploitable areas of science might be identified and commercialised to the benefit of the UK. The overriding conclusion which we draw from our deliberations is that a process be established with the twin objective of (1) gathering information and identifying exploitable areas of science and (2) creating a commitment to translate exploitable science into technology in order to realise commercial processes and products. Although the picture we have obtained is incomplete because of limitations on the resources and time available to us, the impressions are sufficiently clear and revealing to indicate that action must continue in order that the scientific community can strengthen and increase its contribution to the national technological effort. We see greater commercialisation of the results of scientific research as being of the first importance both to increasing the international competitive strength of UK industry, and to increasing the long-term resources available to support science in the UK.

4.1.2. We have not considered the study to be one of picking winners. Rather, we consider that the primary concern at this stage is the need to establish a framework for science decision-making, from which winners are more likely to emerge via market-driven processes.

4.2.1. The report prepared for us by SPRU argued that a major contributory factor in the markedly better performance of Japan over recent years in technology-based industrial sectors related to the difference in level of scientific foresight activities between Japan and other industrialised nations. Although SPRU pointed out that the Japanese approach took insufficient account, for example, of other dimensions relating to technological and industrial development and we have suggested that basic cultural differences and differences in R&D organisations obviate against the wholesale adoption of Japanese methods, we are firmly convinced that the fundamental principle is sound. With growing competition in the world industrialised markets and increasing technological sophistication of the products in those markets, most industrialised countries require a strong science-based economy, decision-making procedures on national science policy must balance judgements on scientific and technical potentials against social and economic developments. The French are developing for their own needs a system similar to that of the Japanese by setting up an international network based on the Centre de Prospective et d' Evaluation (CPE), reporting directly to the Minister of Industry and Research, to assemble relevant databases to assist in the process of long-term scientific and technological forecasting.

4.2.2. During the preparation of this report we heard a number of opinions and views on the way that science policy is developed in the UK, and it is clear that present arrangements are not entirely satisfactory to many of those consulted, particularly in the private sector, who depend on the underpinning science and output of scientific manpower from the public sector. We referred earlier in Chapter 2 to the part which internally and externally motivated criteria should play in considerations of nationally important areas of strategic science. Internally motivated criteria are those traditionally associated with the peer review system which is driven by a process geared to the pursuit of knowledge, and intellectual challenge, in which the recognition of successful achievement is largely in scientific publication and academic peer esteem. Left to itself, such a system does produce externally exploitable work, but often the effects are random and exploitation is a by-product arising fortuitously rather than by judgement. Moreover, the peer review system is particularly weak at exploring the interfaces between different, established branches of science and it is at the boundaries that significant commercial prospects often lie. If science policy is to *increase* the chances of producing advances in understanding which are of industrial and social significance, while at the same time generating substantial intellectual challenge, then that policy must be based upon information and criteria internal to and external to science. Strategic science policy will be facilitated by identifying the range of opinions relevant to the allocation of resources, by science judgements which seek to match scientific opportunity with social and commercial needs over a variety of time-scales.

4.2.3. In every country, science policy is selective insofar as science must compete with other claims on the public purse. Wealthy countries, in particular the USA, can afford to treat the commercial exploitation of science as a random process. An internally directed approach to science policy-making is often wasteful of resources. The objective of strategic policy should be to develop the science and technology to the point at which it can be rapidly and effectively assessed and exploited when market opportunities present themselves. We are convinced that it is feasible to identify the relevant range of opinion through a process of wide consultation and assembly of relevant data. The identification of opinion should involve a continuing dialogue with researchers (new and established), research allocation organisations (Research Council committees) and the industrial research community which iterates between areas of science with promise and those priorities identified by the providers and users of research funds. Above all, though, the process should be continuous. *We recommend therefore, that a process should be established for identifying exploitable areas of science, which has some certainty of continuity, for the long-term economic health of the country.*

4.3. *The Structures and Resources in Support of Science Policy*

4.3.1. In order to achieve the objective outlined above, we consider that four key elements in the process are:

a. the gathering of information on a continuing and permanent basis and its communication to the relevant parties and bodies;

b. the evaluation of relevant opinions and information, and the identification of exploitable scientific areas;

c. the allocation of resources to the priority areas in science;

d. the commitment to exploit the results of science to UK benefit.

Such information gathering and distribution would be a two-way process allowing continuous comment and refinement by the scientific and industrial communities. Broadly based decisions would carry conviction and practitioners as well as potential users would become part of the process. We believe that this would enhance their commitment and confidence in the process. We also believe that this offers the greatest possibility of success in the UK context.

4.3.2. We have concluded that the information necessary to identify exploitable areas of science is acquired at present in a fragmented fashion in the UK. A number of bodies such as ACARD, the ABRC, Royal Society and UGC, together with industry all play a role but rarely do they interact as a combined force to shape policy and direction. Both ACARD and the ABRC tend to operate in a reactive mode. A structure is required which can gather, analyse, prioritise, and direct relevant information into the decision-making machinery. The decision-making process must recognise the three spheres of activity, scientific, technological, and commercial. The structure should link with other bodies, such as the Requirement Board of

DTI and the appropriate scientific bodies of other Government Departments and organisations.

4.3.3. We do not propose that new arrangements are necessary for the mechanisms of funding science. In order to generate a process for identifying exploitable science, resources will be needed to develop the database and to provide judgements on the quality of information. We envisage a small management group to steer the process of identifying exploitable scientific areas independent of the bodies, both public and private, directly concerned with the management of science budgets together with a small group to advise on overall strategy.

4.3.4. If such a process is to be effective in achieving change, it is essential that resources put into R&D must be translated into industrial products, entrepreneurs in science must be brought together with entrepreneurs in industry. That process should be intimately concerned with identifying areas of science with potential, marshalling resources, and executing programmes. The first report of the House of Lords Select Committee on Science and Technology expressed concern that there was too rigid a distinction between basic and applied research and this was noted by Government in their response to the report; the response also suggested that ACARD and ABRC should review the links between basic and applied research and whether these are useful distinctions in the context of the process we have described. We concur with that view and would wish to see a more pluralistic approach to science funding, flexibility should be built into funding mechanisms to allow research programmes to be built up and ended as appropriate. Whether the distinction between basic and applied research is useful in this context should be kept under review.

4.3.5. We discussed briefly in Chapter 1 the relationship of our exercise to the Annual Review of Government-funded R&D, and referred to comments in the Government response (Cmnd 8591) to the first report of the House of Lords Select Committee that the Annual Review analysis should 'not be a facile choice of areas where more money should be spent'.... ' skilful value judgements as to allocation of financial and manpower resources are, however, needed. This will involve distinguishing between vital and dormant areas, identifying gaps, disparities and duplications, and considering the opportunity cost of relinquishing certain areas of research. The emphasis will be on review of long-term plans'. The Annual Review process is now established and we believe that it should now consider long-term R&D plans of Government Departments. The identification of exploitable areas of science should not be independent of the Annual Review.

4.4. *The Nature and content of Research and Development*

4.4.1. The process outlined above should in time lead to a more rational allocation of resources to those science areas of prime national interest. This could require changes in emphasis in the scientific efforts of higher education institutions and Research Councils. Mechanisms may be needed for attracting students to scientific areas of economic promise with intrinsic growth potential. Consideration may be needed of the wider balance of disciplines in the universities. As frontiers expand in new areas, old subjects may be overtaken, for example, and university structures need to keep pace with the rapid advance of knowledge.

4.4.2. We recognise that some areas of science are of potential importance not because of their relevance in terms of direct market applications, but because of other factors such as Government policy, legal constraints, public pressure, etc. Such areas relate particularly to health care, the environment and consumer safety. There are also areas of science and technology which have important social implications, for example, the increasing desire by women for both careers and families and the technology which might assist in the fulfilment of those needs. Society itself creates pressures requiring a scientific or technological response and may also have a direct effect on the process of innovation itself. Thus the current pressures towards alternatives to animal experimentation will have a direct bearing on the science of health care. There is also little doubt that public concern about environmental issues will increase in the next 10–20 years in the UK, rather than diminish. The scientific issues are complex, but such concerns require a reasoned scientific response to avoid the possibility of serious economic consequences and misguided solutions. Careful consideration will be needed of which scientific areas in the environmental field are essential to the UK and which can be left to the international scientific community; for example, geological science may be relevant to waste disposal in the UK but the ‘Greenhouse effect’ is of international interest. The area of product liability has attracted considerable investments in R&D by the private sector in recent years. It is our view that careful and selective attention should be given to non-market forces which will have significant impact on acceptance by society of change and science/technology.

4.5. *Industrial R&D Priorities*

4.5.1. The major manufacturing companies in the UK have quite sophisticated techniques for developing a foresight of science which will be of relevance to their future and are also able to obtain further insights by commissioning work. We have the impression, however, that wide-ranging foresight activities are required throughout the R&D system. The SPRU study suggested that Government should stimulate science and technology forecasting by the provision of incentives (financial or otherwise). We agree that such forecasts are necessary but do not see a role for Government and propose that industry itself should set up the mechanisms for undertaking long-term research forecasting on a permanent and routine basis.

4.5.2. Attention was drawn by SPRU to the need for comprehensive data on the inputs to research, and output data in order to develop sophisticated forecasting techniques. Regular and detailed statistics on R&D in firms, universities and the Research Council institutions are required. The Annual Review of Government-funded R&D is beginning to provide comprehensive statistics on public sector funding of R&D. Some information on industrial R&D support is available but is far from comprehensive both in terms of coverage and detail. Nor does the UK possess the large indigenous data-banks on science and technology, patents, etc, available in Japan and the United States. The UK does not possess the large number of 'think tanks' capable of undertaking assessments of science and technology which the USA and Japan possess. UK databases on science and technology tend to be too academic in nature and appear to be geared primarily to the needs of the specialist researcher than to the broader requirements of industrial research, development and exploitation.

4.6. *Conclusion*

In summary, it is clear that profitable innovation requires the matching of two sets of perceptions:

i. what is possible in scientific and technological terms, and

ii. what is commercially desirable.

The process of identifying exploitable areas of science must draw together these two perceptions, creating a shared vision of the directions in which to develop this dimension of science policy, visions shared by industry, science, and Government which are based upon continual dialogue and discussion. Moreover, most important of all, to support science in terms of its investment potential requires a commitment by all those involved to achieve the promised return to the benefit of a strategic science policy.

PART II. A CASE STUDY

5. Technology: The Bridge Between Markets and Exploitable Science

5.1.1. In Part II we provide a case study to illustrate some of the principles described in Part I of the report. We have chosen information and communication technology to illustrate the approach.

5.1.2. Our central theme is technology as the bridge between science and the production of goods and services which are valued in the market-place. Technology enables the promise of science to be exploited in ways which create employment and raise standards of living in general. Of course, we recognise that the links between science and its commercial exploitation are complex and not unidirectional. New technologies are rarely if ever fully developed when they are first introduced commercially. A typical history of a new technology or industrial activity involves a sequence of advances in products and processes, advances which are stimulated by market pressures and by opportunities opened up by new scientific developments. Furthermore, the extent of commercial application of any one technology depends on the technologies with which it is in competition, and it is often held back by a lack of development in complementary technologies.

5.1.3. We found it useful to identify certain trends impinging on the exploitation of science. Our use of the word trend needs to be clarified. The primary trends are those developments in science, economic and social environments which alter the balance of relative commercial returns to the development of different technologies. Thus, changes in the population, and its age, structure and advances in fundamental knowledge are examples of primary trends which will greatly influence the commercial development of medical technology. Environmental attitudes on waste disposal will greatly influence the application of nuclear technology. Similarly, the persistent tendency of real wages to rise, and changes in the relative availability of different materials and sources of energy continually generate new opportunities for technological development.

5.1.4. These and other primary trends induce secondary trends in patterns of technological development, for example, more fuel efficient aero-engine technology, more efficient measuring techniques, the displacement of paper-based communications technology with electronics-based communications, but they are consequential trends arising from the pressures and opportunities created by economic, social and scientific change. In what follows, we shall be concerned almost exclusively with primary trends.

5.1.5. In Part I we suggested that the following elements are required to identify an area of exploitable science:

a. Economic and social pressures affecting the returns from developing different technologies;

b. The technological solutions which are likely to arise in response to the pressures; and

c. The areas of science likely to underpin the required advances in technology.

5.1.6. We do not believe that actual developments in science, technology, and markets follow a simple linear trend and the schematic representation shown at the end of Chapter 6 is used to illustrate the complexity of relationships between markets, technology and science. The one shown relates to communications but similar models could be drawn up for other areas, for example, energy, environment, transportation, health, etc. At the centre of the model are currently discernible or potential economic activities possibly, surrounded by technological applications broadly relevant to such activities which, in turn, are linked on the outside to the scientific activities from which new technologies will arise. For some activities there is little associated science, although links with technology might be greater.

General Trends

5.2.1. Various trends in society are so broad that they influence many areas of social and economic activity. The following such trends are the more obvious ones—

i. Demography — total population, age structure, distribution, household composition, birth rate, marital status, etc;

ii. Employment rates — work-force size, activity rate, unemployment, labour mobility and factors affecting, age of work-force, sectoral demands, skills availability, etc;

iii. Attitudes to work — motivation, work values and rewards, incentives, work quality and ethic, entrepreneurship, training, life-styles, etc;

iv. Work forms — full-time/part-time work, job-sharing, self-employment, formal work/informal work, centralisation, mobility;

v. Reaction to change — acceptance of new technology, attitudes to industry, need for apparent stability, environmental concerns, security, etc.

5.2.2. Other broad trends are also clearly discernible, for example, the increasing desire of people for autonomy, to act independently, and to have greater control over their own lives. Such trends will continue to affect the development of communications and transportation technologies in particular. The impact of single-issue pressure groups whether institution-based or not may have unforeseen results on societal and technological developments. Groups in the legal, trade, industrial, business, scientific, or medical professions are all able to exert pressures which affect the direction and rate of technological development. Government itself is also a major influence.

5.2.3. A major preoccupation or trend in recent years relates to aspects of security, ranging from the safeguard of individuals and their rights or property to the protection of a scientific advance or intellectual concept and various aspects of civil, national and international security. The increasing penetration of electronic technology in the activities of business, industry and society generally will require technological responses and present opportunities. Similarly an ageing population may demand an increase in security consciousness.

5.2.4. General trends in the broad allocation of consumer expenditure are relevant. In 1983, consumers' expenditure accounted for about 60% of Gross Domestic Product (GDP). The proportion of consumers' expenditure in various categories was as follows:

	% of total consumer expenditure at current prices		Consumers' expenditure indexed at constant 1980 prices	
	1972	1983	1972	1983
Food	18.3	15.0	96	101
Alcoholic drink	7.2	7.3	79	98
Tobacco	4.5	3.4	104	85
Clothing & Footwear	8.3	6.6	82	110
Housing	12.9	15.0	85	104
Fuel & Power	4.4	5.2	94	98
Household goods & Services	8.0	6.8	99	109
Transport & Communication	14.4	17.1	92	110
Recreation, Entertainment and Education	9.0	9.1	75	107
Other goods, services and adjustments	13.2	14.5	90	100

The most significant trends in the last ten years has been the large increase in consumers' expenditure on transport and telecommunications, whilst that spent on tobacco and non-electronic media has decreased. The proportion of consumer expenditure on food fell whilst that spent on housing rose.

5.2.5. We have side-stepped many complex issues by focussing on broadly defined primary trends. A more detailed identification of strategic promise in science would have to look in much greater detail at developments in particular markets, in the profitability of different technological solutions, and the contributions which different sciences would make to those solutions.

6. Markets, technology and science in communications and information

An increasingly complex society is becoming more and more dependent on its knowledge. The planning of a business enterprise depends on the data it gathers on markets and competition. The treatment of a malfunctioning body depends on diagnosis. The science of data handling has progressed greatly in the last ten years largely due to an improved capability for processing information in electronic systems. The improvement in processing has justified improvements in acquiring this data, for the two should go hand in hand — there is little point in gathering data which cannot be used.

6.1. *Market Trends*

6.1.1. The two most significant trends which have stimulated developments in new technologies in communications and information in recent years are:

a. rising real incomes and demand for entertainment, both home-based entertainment and greater variety in entertainment.

b. information activities are historically labour-intensive but rising real wages has led to continuous cost-cutting pressure to reduce employment.

6.1.2. So far as markets for information are concerned, it is possible to distinguish different types of information:

i. Information as decision-making input to business;

ii. Information which is the final commodity:

  a. scientific and technological information
  b. entertainment;

iii. Information as a public good;

iv. Difficulty of maintaining property rights in information, combined with the fact that information is expensive to produce but cheap to copy.

6.1.3. The increasing complexity of modern society on both the domestic and international scale raises the amount of information required for it to work efficiently. The information society depends on:

a. Acquisition of information
b. Storage and processing of information
c. Communications.

The development of computers has provided greater processing and storage power and has led to the pressures behind the development of digital communications systems. However, these technologies acquire significance only in so far as they displace existing activities. Different types of displacement are:

a. a trend away from paper-based storage and communications, this has implications for paper-based industries;

b. displacement of analogue communications systems by digital systems eg digitally-based networks.

6.1.4. The availability of communication technologies and their widespread use, will permeate practically all human endeavours. The key feature of the information society is the controlled acquisition and accumulation of knowledge in communication systems and amplification of the processing techniques with which to use that acquired knowledge. The support of knowledge systems themselves thus becomes a major driving force of economic activity.

6.1.5. The proliferation of communication and transfer mechanisms will radically transform transactions between individuals and groups in society not only in the private services sectors of the economy but also to education, public sector services, private communication, and many others. One aspect of such development concerns the problem of public access to information. Protection of privacy, the consent of individuals to the use of stored information and protection of data from external penetration or internal leakage from communication systems, provide important examples.

6.1.6. Better communications will increase the possibility of working from the home, which might have some effect on travel and commuting. The ability to work, with the help of communications, from home will also permit growing numbers of women to continue working after starting their families. This trend, already strong in the field of software, may well spread to other economic fields.

6.1.7. Video recording and transmission is in its infancy and business opportunities for future video applications in education, counselling, advisory service, selling, etc are clearly possible. However, technological innovation in communications is unlikely to proceed linearly and advances are likely to occur in fits and starts. For example, experiments have been started in electronic shopping and marketing but it is highly unlikely that people will wish to do all their shopping electronically although for some sections of the populations and for some transactions it will be advantageous to do so. Similarly teleconferencing will not totally replace the face to face business meeting, since it will probably be found to be inappropriate or inadequate in many circumstances.

6.1.8. Cable television also offers many options for development. Apart from delivering locally produced programmes such systems can produce a diversity of television communication ranging from business, religious, news services to health, childrens, scientific, art or other networks. Already in the USA cable networks are drawing audiences in the prime viewing times from the national television companies and it has been forecast that in the next decade such companies may well have only 50% of the total television audience.

6.1.9. The rate of change in communications technology has begun to impact at a local level on paper-based systems and will expand to dominate more widely distributed systems. These technologies especially increase the speed of flow through information channels. As a consequence, information is being generated at rates previously unsurpassed and uncontrolled, unorganised information could impede the exploitation of the developing knowledge base. Developments in modern information technology will therefore have a vital role to play in the selection of information. On-line database technology will be essential to the wide availability of required useful information and dissemination of knowledge. Wider access to such databases will require development of much better software.

6.1.10. Global communications with a variety of objectives will be of increasing importance, and the satellite will have a key role to play. Satellite technology is advancing rapidly and now incorporates the functions of ground stations. As demonstrated recently the development of space shuttles for the retrieval and servicing of satellites will have relevance for the information economy as well as for space exploration. The two important aspects of satellite technology relate to direct communication of both voice and video and the ability of satellites to take in data — this has implications in the area of remote sensing. One major effect of the growth in world communications technology will be the increasing internationalisation of business opportunities. Thus the satellite will allow information to be instantaneously distributed and shared round the world.

6.1.11. Growth in communications may see greater internationalisation of national languages. It is unlikely that a world language will arise although English may be used increasingly as an international business and legal language. As the global economy becomes increasingly interdependent, national cultural and linguistic traditions may well be reinforced, as they have been in Europe since the formation of the European Community. Communications technology may provide, for example, the simultaneous automatic machine translation of national languages, for broadcasting world-wide, so facilitating communication between national communities.

6.1.12. In summary, market directions will lead to the continuing need for technological innovation in:

Electronic Information Services — videotex, viewdata, Prestel, Teletext, cabletext, interactive video, video-cassettes

Home computing — hardware, interfaces, telecomputing, software

Enhanced communications — cellular radio, electronic mail, teleconferencing

Electronic banking and financial services — automated money tellers (AMT's), robot banking, smart cards, EFTPOS

Communications Technology in Retailing — information service, teleshopping

Electronic entertainment and education — Cable TV, video, satellites (including ground- based infrastructure)

The foregoing developments may be attributed to the tendency of society to increasing intensiveness in information requirements whilst developments in science have reduced substantially the cost of transmitting and processing information; these are the two most fertile trends in stimulating new communications technologies.

6.2. *The Acquisition and Handling of Information*

6.2.1. In the context in which we analyse the topic, we consider "information" to be made up of both data and knowledge and a series of rules for combining them. It is obvious that humans exploit all three in deciding on a course of action. Computers are not yet as good as humans in coming to judgements because programming is still at an early stage of development. The handling of information may be broken down into five parts, each a subject in its own right. These are:

1. Acquisition
2. Organisation
3. Processing

4. Transmission
5. Exploitation

6.2.2. The *acquisition* of data depends on sensors, which are now becoming extremely sophisticated, often involving an overlap between two or more sciences, chemistry, physics, biology and electronics. Not only is progress being made to measure directly parameters which were previously the target of difficult laboratory experiments, but also in detecting traces of elements or molecules — sometimes as few as five atoms. Moreover, we can do this, with exceptional rapidity, often in real time.

6.2.3. The *organisation* of the information is an important step in understanding its importance. It can be classified and compared with information already held in the system memory. The size and management of the knowledge base now becomes critical. Cognitive Science and Artificial Intelligence will play key roles in the improvement of information handling.

6.2.4. Data *processing* is generally recognised as the feature by which electronic computers have made their major impact. But present computers process information step by step, or sequentially, by the so-called Von Neumann process. Future progress may well depend on the ability to master parallel processing techniques, with processing units distributed around the computer, or by optical processing.

6.2.5. *Transmission* of information locally, nationally, or internationally is fundamental to data handling. There have been two hardware developments which have completely changed the nature of data transmission, and will determine the shape of the next ten years. The first is optical fibre transmission, and the second satellite communications. The ability to observe the world as a whole gives us not just a system of communications but also an ability to sense remotely, to gather data which was previously not available.

6.2.6. The final stage of *exploitation* can be divided into two classes. Sometimes data are exploited in a machine, such as a robot, without human intervention. The growing fields of robotics and computer aided (or integrated) manufacturing are examples. The other class is direct exploitation, where a human is expected to interact with the system. The conclusions emerging from the electronics are presented to the eye or ear of the operator. This interaction can be cyclic, particularly with voice command to the electronic system acting as the input.

6.2.7. Much of the progress expected in data handling will depend on the development of new materials.

6.3. *Electronic Materials*

6.3.1. For the next decade perhaps, silicon is likely to continue to hold its pre-eminent position as a material in the electronics industry. But there are many other binary and ternary solids which are candidates for development and exploitation eg GaASm, GaAlAs, Zns.

6.3.2. Naturally, developments in the field of data acquisition and handling also rely on progress in other aspects of electronic materials science eg fibre optics, advanced lithography and large area displays. Other challenges to the materials technologists will include the integration of electronic and opto-electronic devices on the same chip and the use of molecular systems to transport excitation between systems currently employed in integrated circuits. Theoretical studies will be required to help gain a better understanding of optical and charge transport effects on small time and distance scales.

6.3.3. The two areas discussed below should serve to illustrate the need for more research on electronic materials. There is already considerable interest in the first of the topics selected and commercial devices are likely to emerge during the next decade. The second is rather more speculative and discusses some facets of micro-electronics to which many (untapped) inorganic extended solids and organic molecular chemistry could make a decisive contribution.

Quantum Well and Low Dimensional Inorganic Structures

6.3.4. Recent advances in semi-conductor materials, growth, and assessment techniques have made possible the creation of ultra-thin multilayer structures with a periodicity of the order of a few nanometres. In these structures the composition or the electrical doping may be varied to produce heterojunctions, quantum wells, and superlattices in which quantum effects determine the electronic energy levels. These quantum well (QW) structures exhibit new effects not present in bulk solids, and combinations of known properties, which offer a wide range of novel device possibilities. These developments may be regarded as a new branch of research in both basic physics and device physics or solid state electronics. Device applications will include both ''photonics'' such as lasers and detectors whose wavelength may be selected during growth for optimum performance, and a wide range of electronic devices. Industrial applications will require further investment in sophisticated growth techniques such as molecular beam epitaxy (MBE) and metal-organic chemical vapour deposition (MOVCD).

6.4. *Molecular and Supermolecular Electronics*

6.4.1. Electronic and optical devices used in the microelectronics and communications industries rely largely on inorganic materials for their operation. However, the richness of the variety of molecular materials, especially of the organic solid state, offers a range of possibilities for development which contrasts markedly with the relative paucity of possibilities achievable with the elemental crystalline inorganic structures of present day electronics. Molecular materials vary in complexity from simple molecules through molecular crystals and polymers to complex macromolecules such as the proteins and nucleic acids. The consensus forming in the scientific community is that the wide range of structure and complexity of molecular materials coupled with the ability to enlist the techniques of synthetic organic chemistry will make it possible to develop materials with specific properties tailored to specific needs. This will pave the way for the exploitation of new and exciting phenomena.

6.4.2. Research on molecular electronics (defined as the systematic exploitation of organic molecular materials in the field of electronics) is of very wide scope and is inevitably interdisciplinary. It has three main but related aspects; the design and preparation of new molecular materials, the study and optimization of applicable properties, and the development of practical devices. Materials and properties of particular interest include: *Liquid* crystals, both for their now familiar use in displays and for their potential use in switching and memory elements; *Langmuir-Blodgett* films with the natural molecular orientation within each monolayer, the control over molecular architecture, and the precise definition of thickness, whose potential is being explored in applied areas such as ferroelectricity, electro-optics, lithography etc; *Polymeric photoconductors and semiconductors* which can be doped to increase their response, yielding photocopying systems and novel storage battery materials which need contain no metal; *Organic metals* and superconductors, of potential value in connecting active materials and conventional semiconducting substrates; *Resist materials* which react in electron beams and permit microlithography with features approaching molecular dimensions; *Photochromic and electrochromic* materials which change colour rapidly to produce stable high-density information storage systems; *Pyroelectric and piezoelectric* materials useful in detectors and transducers such as the electret microphone; *Biological molecules* which can be used as sensors when immobilized on a semiconductor substrate; *Electo-optic nonlinear* materials which combine high response and stability useful in integrated optics and opto-electronics.

6.4.3. It is now recognised that modern day computers based on silicon are reaching the frontiers of technology and suffer from disadvantages in many respects. These include the limits imposed by heat dissipation, sequentiality, effective programmability, efficiency and sensitivity. It may be possible to overcome these limitations by building a computer out of molecular components. For example enzymatic reactions in biological systems dissipate very little energy and can perform, reversibly a tactile pattern recognition task that would involve many steps for a digital computer. The prospect of a supermolecular information processor brings the whole range of scientific questions usually considered in the field of molecular electronics into sharper focus, viz molecular structure, switching, interactions, transport and input/output by optical or electronic means. It seems likely that the facility of biological molecules to self assemble into complex useful structures is a worthy target for possible utilization in future technologies. This ultimate expression of molecular electronics is a long way into the future. However, it is clear that the study progression from current technologies to molecular electronics and subsequently to supermolecular electronic systems will draw on a very broad science base involving biology, chemistry, computer science, electronic engineering, materials science and physics.

6.5. *Data Acquisition*

a. Sensors

6.5.1. The present standard of sensors and instrumentation in most of UK industry is weak and rudimentary except in the growing area of biotechnology. Therefore, it is hardly surprising that the majority of organisations which we have visited have highlighted the need for improved understanding and development of sensors. In order to produce a reliable device it is important to consider the overall system. That is, the transducer and the associated instrumentation cannot be divorced from the sensor at the front end. Moreover, advances in microprocessor instrumentation now permit more sophisticated control of the sensor, thereby conferring greater reliability and specificity.

6.5.2. Several Research Council sub-committees have expressed the requirement for programmes of fundamental research directed towards the applications of specific sensors: for example, medical scientists are concerned about the development of biosensors which could lead to completely new clinical procedures; chemical engineers are developing an interest in the use of sensors for process control; and biotechnologists require improved sensors for detecting minute quantities of organic molecules. There is no doubt that research will need to be multidisciplinary. It will impinge on the activities of solid state physicists, electronic engineers, biologists and enzyme, polymer; and electro- and software chemists. In some areas such as speech input and recognition, it will require signal processing skills of the micro-electronics engineer to integrate the sensor and the detector on the same microchip. The development of sensory techniques will also have an impact on the production of robots in manufacturing technology.

6.5.3. An indication of the wide range of basic scientific research required for the development of improved sensors can be gained by studying requirements in the medical field. Here, priorities vary from cheap and reliable *in vitro* sensors for use in the home or hospital ward, to more sophisticated ones for *in vivo* investigations, eg blood monitoring. Chemically sensitive semiconductor devices utilizing antibody-antigen reactions and novel organic materials which react highly specifically and reversibly (such as receptor proteins) are required. In order to produce biological sensors it will be necessary to develop surfaces compatible with proteins and other biological molecules, to investigate means of immobilizing ionophores in thin films and control the deposition of the active-species onto specific sections of a micro-device. Research will also be required into the physical properties of novel transducers to be used in conjunction with the sensor to provide reliable, on-line, real-time instruments, eg ion sensitive field effect transistors, optical fibre sensors and piezo-electric devices.

b. New Analytical Techniques

6.5.4. Advances in instrumentation and in analytical techniques applicable in many disciplines continually emerge as a result of the discovery of new physical effects and principles. We only describe briefly a few examples here and the reader is advised to consult the published literature for more information. For example, the resolution of electronic microscopes is being greatly extended, novel X-ray techniques are emerging based on synchrotron storage rings, nuclear magnetic resonance is now being used successfully in tomography, and surface analytical techniques such as photoemission are currently being refined for the study of thin films and catalysts.

6.5.5. Contemporary micro-electronics is already making powerful demands on existing methods for characterising materials and devices. Molecular electronics will demand molecular scales of resolution in chemical analysis; new techniques are required to study ultra-thin film on substrates, solid-liquid interfaces, surface phase transitions, low dimensional structures, nanomole quantities of molecules etc. UK physicists have an excellent reputation in this type of research which ultimately leads to a profitable export industry in high quality instruments. The UK has been and remains a world leader in the production and export of mass spectrometer and photoelectron spectroscopic equipment.

6.6. *Organisation*

a. Memory

6.6.1. Data storage for computers represents the largest single area of activity in current semiconductor research, the objective being to produce larger and faster memories, with corresponding reductions in the "cost per bit" of information stored. There is world-wide recognition of the need for this improvement in memory technology and a large number of major companies are carrying out research in the area. One result of this wide recognition is that memory products have become a commodity on a world-wide scale with cyclic episodes of shortage and glut.

6.6.2. Memories however form an essential element in all computers and availability is of fundamental importance. The current emphasis on support for this work given by the Alvey committee acknowledges the key strategic importance of UK sources of this commodity to reduce vulnerability to fluctuations in supply from Japanese and American sources.

6.6.3. In addition to semiconductor based memories the exceptionally large capacity available in optical memories (laser/disc systems) is beginning to be the subject of significant research work. There is the prospect that for some applications large optical memories could displace semiconductors.

b. Memory Organisation

6.6.4. With the growing availability of ever larger memories there is increasing interest in the optimal organisation of these memories to make better use of the power available. The human brain is one evident example of the efficient organisation of a massive memory base in which information is retrieved by reference to the nature of the information rather than by making use of the memory 'address' in which the information is stored.

6.6.5. As a pointer to methods of organisation of large memories, therefore, much attention and current research is being directed in the area of cognitive science to begin to understand how the human brain and memory is used to achieve such functions as learning language, recognising speech, recalling experience, etc.

c. Knowledge Base Organisation

6.6.6. At a less anthropomorphic level, experience is rapidly increasing in the construction and manipulation of large accumulations of data and knowledge in existing computer databases. These provide plenty of raw material to enable experiments on the most efficient ways of gaining access to these data. Research on database management is of substantial commercial interest and will undoubtedly result in new products of significant commercial potential.

6.6.7. More recently, the value of accumulations of knowledge has begun to be recognised — or rules from experience of the form 'if A and B then C'.

Work with knowledge sets of this sort is the basis of current research in the development and application of Expert Systems. This is widely recognised as an area with huge commercial potential enabling the provision of automated expert advice and guidance in areas such as medical, legal and military applications. With the assistance of such a system a comparative non-expert could provide the effective skill of a highly trained and experienced specialist.

6.6.8. Further development of this approach leads to the area of Artificial Intelligence where advice, decisions and subsequent actions may be made by the computer without the intervention of the human operator. Again it is widely acknowledged that the commercial potential of such systems is very large indeed.

6.7. *Processing*

a. Computers

6.7.1. Traditional computers have been organised with one '*central* processing unit' (CPU) which carries out one instruction after another (generally operations on data which has been recalled from and is subsequently put back to memory). The sequence of instructions executed by the CPU is exactly determined by a precisely written program which is predetermined by the computer programmer. This consequential instruction approach is generally known by the name of its inventor — von Neumann.

6.7.2. Current developmental activity in achieving greater processing power has largely concentrated on increasing the speed of operation of the CPU, enabling it to carry out more instructions per second, and also by increasing the scope and variety of the operations which it is able to execute. Although substantial increases in computer power have been achieved by this route there are clearly upper limits on achievable electronic speeds and on a sensible level of complexity for the processor.

b. Distributed Processing

6.7.3. With the availability of reasonably cheap semiconductor processors there has been a natural move towards the incorporation of more than one CPU in a single computer. The implication of this is that a number of commands or instructions can be executed in parallel, clearly giving rise to the prospect of greatly increased effective speeds for carrying out computing tasks.

6.7.4. However, the majority of computer scientists have been trained along von Neumann lines and so have considerable difficulty embarking on the design and organisation of a machine which has no single CPU. There is no corresponding standard approach to the electronics organisation of such a computer and considerable amounts of research will be required to develop effective use of multiple distributed processors. In general terms, there is an assumption that in lieu of one very large memory and one powerful CPU, future computers will contain a large number of processing units each associated with a comparatively smaller segment of memory. Research work in this area has just begun and success in this area will be key in the successful design of the next generation of computers.

c. Software

6.7.5. Implicit in the trend to distributed processing approaches is the need for a corresponding new generation of software. The key question is the optimum way to organise a set of commands to a whole series of processors so as to achieve the optimum execution of a computing task. Faced with liberation from the classic serial von Neumann approach there is no standard method to adopt and at the present time the ability to define effective techniques is lacking. It is almost as though software writers had been taken back to the late 1940s and begun the task of organising a computer all over again.

6.7.6. As a result the whole area of software strategy, languages and operating systems for effective data processing is at a highly embryonic stage but is clearly the key to successful exploitation of fifth generation computers.

d. Other Processing Approaches

6.7.7. For some particular applications specialised approaches to processing are possible. For example, it is currently feasible to take an optical image and manipulate it in the optical domain in order to extract fine detail information only. This need involve no digital data processing of any kind. Another application is the identification of small changes between pairs of images which is a technique currently exploited in component stress analysis and in security applications.

6.7.8. Since optical records contain very large amounts of information when expressed in electronic bit terms, and there are vast amounts of image information which require processing (eg remote sensing satellites looking for weather or resources) then this technique extends the prospect of much more speedy information processing than would be possible in a digital computer.

For this reason, this and similar specialised techniques are the subject of much current research.

6.8. *Transmission*

6.8.1. The last twenty years has seen the habits of the community changing dramatically, with a move away from hard copy to electronic pictures, from books, and to some extent, newspapers to TV. This ability to bring information directly and cheaply into the home has by no means reached a plateau, consumer spending on TV and related hardware having doubled in the last ten years, and still increasing at 7% per annum in real terms. In spite of this growth, the consumer spends more on letters and telephones than on TV, though expenditure on communications is increasing quite slowly. The improvements in the telephone system in the past ten years have been largely due to the substitution of modern hardware into the existing system, electronic exchanges, transistorised repeaters, microwave links. The first results of revolutionary changes, with progress in optical fibre systems and satellite communications, are beginning to be realised. These will lead to cheaper communications, particularly over long distances.

a. Optical Fibre Communications

6.8.2. It is now possible to impress a light signal into an optical fibre, and detect it 100 kms away, without any amplification en route. Moreover, the system gives many times more bandwidth than conventional cable, so that the same fibre will hold many conversations. The cost of communications, plus electronic techniques for compression of data, will make videophones practical for the consumer.

6.8.3. Improvements in fibres should allow repeaterless transmission under the Atlantic within 10 years, giving considerable competition to satellite systems. The ability of optical fibres to pass information along many close-packed channels without mutual interference can be exploited in many ways, one being in phased-array radar systems. Remote control, either by free-space borne infra-red, or local miniature microwave systems, will become commonplace.

b. Satellite Communications

6.8.4. The increasing number and use of satellites in data transmission makes them an important feature for us to consider. A well-publicised use — as telephone repeaters — will come under increased competition from optical fibres. TV distribution in countries with a dispersed population will expand. A development with a pronounced effect on the Third World will be direct transmission from source to set. The low noise amplifiers that are necessary have recently become available, but their cost is still too high for widespread use in poor countries, who need them most. This will change.

6.8.5. However, satellites, and communication via them, can take on a more novel and extremely important role, for the satellite can be used on an observation platform for monitoring the atmosphere, the sea, and the land.

c. *Remote Sensing*

6.8.6. The development of sensors and even more of better processing equipment has made remote sensing a subject with great potential. There will, no doubt, be continued interest in remote sensing by aeroplane and further development of sensors which will make this a useful method for *ad hoc* service inspection. But the main interest centres on remote sensing by satellite because of the long term continuous surveillance of virtually all parts of the earth's surface that is thereby possible. With electromagnetic sensors, information is yielded by every pass but with operational and infra-red sensors a clear sky is required.

6.8.7. Remote sensing has been very useful in the geographical search for mineral and similar sources, although apart from changes in the time of day, and therefore illumination, an unchanging situation is viewed and very few satellite passes are sufficient. Further opportunities for such uses of remote sensors will depend on the development of new sensors. It is different when the object being viewed is changing. Meteorological satellites are well developed, but satellite study of the oceans for surveys, current and surface temperature is at an early stage; instrumentation, also, is not yet sufficiently advanced. The monitoring of the state and condition of crops such as sugar beet, coffee, sugar, wheat, giving greater understanding of the progress of plantations and agriculture will shortly arise with enormous implications for commodity markets. No doubt there will be political and legal problems, but it is expected that these will, in due course, be resolved.

6.8.8. The development of satellite borne sensors is an important field to which the UK has, so far, only made a relatively modest contribution outside specific areas of great scientific importance, such as, in particular, the upper atmosphere and some aspects of sea surface screening. There may well be scope for a broadening of the UK's effort in the sensor field.

6.8.9. Though it is easy to be distracted into believing that the satellite and its instruments are the most interesting parts of the enterprise, the downstream element is likely to predominate. Computerised processing is required not only for the flood of data generated by a satellite, but particularly for embedding this new information in information only attainable by other sensors and methods. Ultimately this union will require a body of skilled interpreters. The development of interpretation techniques and methods, and producing sufficient numbers of people able to participate in these economically very important activities is a major challenge, as is the link with new customers and increasing their awareness of the value which can be added to their business by information obtained from satellites.

d. Navigation

6.8.10. The position of an object on earth can be determined extremely accurately by a satellite. Ship navigation can clearly benefit from such a system, but there are also possibilities for vehicle course control in areas where a local transmission system for navigation is impracticable.

6.9. *Exploitation*

a. Exploitation and Interpretation

6.9.1. It is only by the practical applications of information acquisition and handling that users will see worthwhile benefits. The scope for useful applications grows as technical capability for information handling grows. Early computers had limited (but speedy) number manipulation and storage capability. They were therefore applied to critical calculation tasks, where the principle ability of the computer was directly exploited.

6.9.2. As mass storage of information became technically feasible, user applications were able to expand from high speed arithmetic to the holding and modifying of very large collections of information. Clearing banks' customer account records and airlines' reservation systems are examples of user operations, once performed manually, and now exclusively handled by computers.

6.9.3. Today, we have available even more abundant storage and processing capacity enabling applications to be designed which go beyond large but intrinsically simple tasks, towards functions previously only carried out by the human brain, involving, for example, interpretation and judgement. As yet such applications are in early stages of development but their common characteristic is that they are used in an interactive mode with the human operator. Interim results are made available to the user, who then has an opportunity to confirm, challenge or modify those results before further work is carried out. A working dialogue between computer and user then allows a combination of the intrinsic abilities of each.

6.9.4. At present we are learning how best to store and handle information to support this dialogue. Considerable work is required to develop efficient ways to extract human knowledge in a form suitable for machine storage; to identify the rules used in forming judgements such that they can be automated; and to facilitate a ready dialogue between computer and user employing the ear, eye and voice.

6.9.5. A small number of such systems operating in limited environments exist at present but, for example, a full scope medical diagnosis ability equivalent to a general practitioner will require at least a decade of development work.

6.9.6. Development will be required therefore in: knowledge elicitation; analysis of decision and judgement rules; high resolution visual displays which are capable of accepting user input via touch; voice synthesis techniques for audio output; speech recognition techniques to allow direct voice input and command; and natural language working to allow the dialogue to take place in common usage English.

6.9.7. The information filtered and assessed by the electronic systems is then available for use. The direct use, in an automatic engine or robot, is already becoming normal practice in manufacture. The indirect use, via a human being, is also of critical importance. Two systems of output presentation are available, and both will make great strides in the next few years. We describe these before enlarging on direct exploitation in manufacture.

b. Visual displays

6.9.8. Optical presentation, the electronic display, has for many years relied on the cathode ray tube (CRT). The television monitor is a refined instrument, but its perforamce is now outstripped by the capabilities of the camera and the transmission and processing electronics. There is a demand for flatter systems, with a resolution of 1200 lines, and an area of 1 metre square. It is unlikely that a variant of the shadow-mask tube will meet this specification, but it would be surprising if some satisfactory system were not evolved in the next 20 years.

6.9.9. On a less ambitious scale, we can see flat panel displays dominating the market for word processors and vehicle instrument panels, and it is likely they will replace cathode ray tubes in most computers. They will take a fraction of the portable TV market, but their extra convenience will not generally outweigh the poorer picture they give.

6.9.10. Both types of display, CRT and flat panel, will become completely interactive, with the operator communicating by touch with the electronic system, and, possibly, to some home base. Home voting on important — or trivial — topics will be simple and cheap. This is likely to become an important technique for market surveys, home shopping and advertisement monitoring.

c. *Aural Presentation*

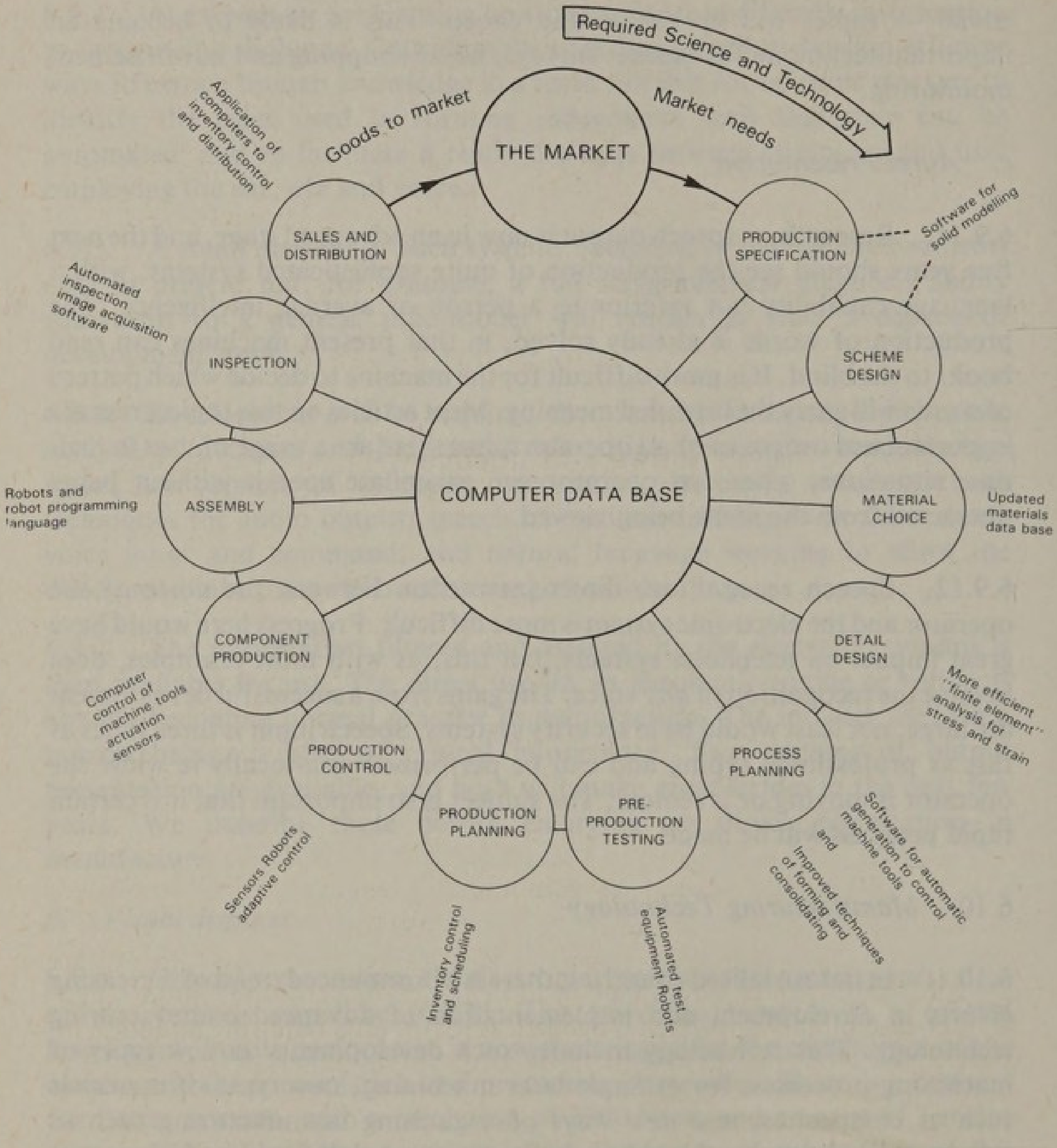
6.9.11. Research on speech output is now in an advanced stage, and the next five years should see the production of quite sophisticated systems, with a language capability not inferior to a person of average intelligence. The production of words is already solved, in that present machines can read books to the blind. It is more difficult for the machine to decide which pattern of words will carry the intended meaning. Most articles on this topic stress the importance of output to blind operators, but there are a range of uses in real-time situations, where an operator can assimilate speech without being distracted from the scene being viewed.

6.9.12. Speech recognition, direct interaction between the voice of the operator and the electronic system is more difficult. Progress here would have great impact on telephone systems, but this, as with most examples, does involve the recognition of *any* voice. The gains from a successful development are large, not least would be in security systems. Speech input is three times as fast as professional typing and can be performed non-locally ie while the operator is moving or is remote. The subject is so important that it is certain rapid progress will be made.

6.10. *Manufacturing Technology*

6.10.1. In industrialised countries, there is a pronounced trend of increasing efforts in development and implementation of advanced manufacturing technology. This technology includes such developments as new types of machining processes, for example laser machining, new types of materials such as composites, and new ways of organising manufacturing such as cellular manufacturing. However, by far the most significant and important type of advanced manufacturing technology being developed and implemented today is computer integrated design and manufacture. The objective of such advanced manufacturing technology are:

a. higher quality products straight from the 'drawing board;'
b. reduced development time;
c. reduced testing time;
d. reduced machine tool non-productive time.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Market needs
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SALES AND DISTRIBUTION
PRODUCTION SPECIFICATION
SCHEME DESIGN
MATERIAL CHOICE
DETAIL DESIGN
PROCESS PLANNING
PRE-PRODUCTION TESTING
PRODUCTION PLANNING
PRODUCTION CONTROL
COMPONENT PRODUCTION
ASSEMBLY
INSPECTION
Application of computers to inventory control and distribution
Software for solid modelling
Updated materials data base
More efficient "finite element" analysis for stress and strain
Software for automatic generation to control machine tools
and
Improved techniques of forming and consolidating
Automated test equipment Robots
Inventory control and scheduling
Sensors Robots adaptive control
Computer control of machine tools actuation sensors
Robots and robot programming language
Automated inspection image acquisition software

Computer Integrated Manufacturing (CIM)

6.10.2. Manufacturing engineering in the United Kingdom will increasingly be required to consider the totality of the process from raw material to product in much the same way as chemical engineering does at the present time. The traditional compartmentalisation between design and its methodology, production technology, quality control, and the man-machine interface will be broken down and transformed into an integrated system. Such integrations will be made possible by co-ordination of all aspects of the manufacturing system by extensive use of computerised databases shared across many functions (see diagram). A flexibly automated factory will use computers in virtually all aspects of manufacturing, integrating production functions with planning and control functions. The application of a flexible automation system may well extend beyond the site of production to co-ordinate with sales and even the retail point. The designer will generate the database which will define the component. This database can be used with finite element analysis software to determine the stresses, strains and deformations. Solid modelling techniques will be used to examine clearances and the stylistic design. The design of press tools can be automatically generated from the database. The programs for control of machine tools in the manufacturing process will also be automatically generated. From this design database and the market requirements we shall generate inventory control and shop floor scheduling. The manufacturing processes in turn will be automated by robotic tool changing on machines, automated controlled storage and retrieval systems for components, and automated inspection of the finished product by robot.

Automatic Processing

6.10.3. The rapid increase in computing power cannot be exploited effectively if it is not matched by a corresponding improvement in the quality of the input data, especially in the field of automatic process monitoring control. There is an apparent lack of information on sensor technology and an inter-disciplinary approach is needed. A major area requiring attention in sensor research is concerned with the development of materials to make them cheaper, more robust and more capable of working in hostile environments for long periods without servicing. Much of the basic science exists, it is the translation into hardware and useable technology which is mainly required. Areas of science and technology which are of importance to the development of integrated design and manufacturing systems are —

1. Software for solid modelling
2. Object recognition and image acquisition
3. Management of large databases
4. Actuators
5. Sensors

6.11. *Mathematics which underpins developing areas in the acquisition and handling of information*

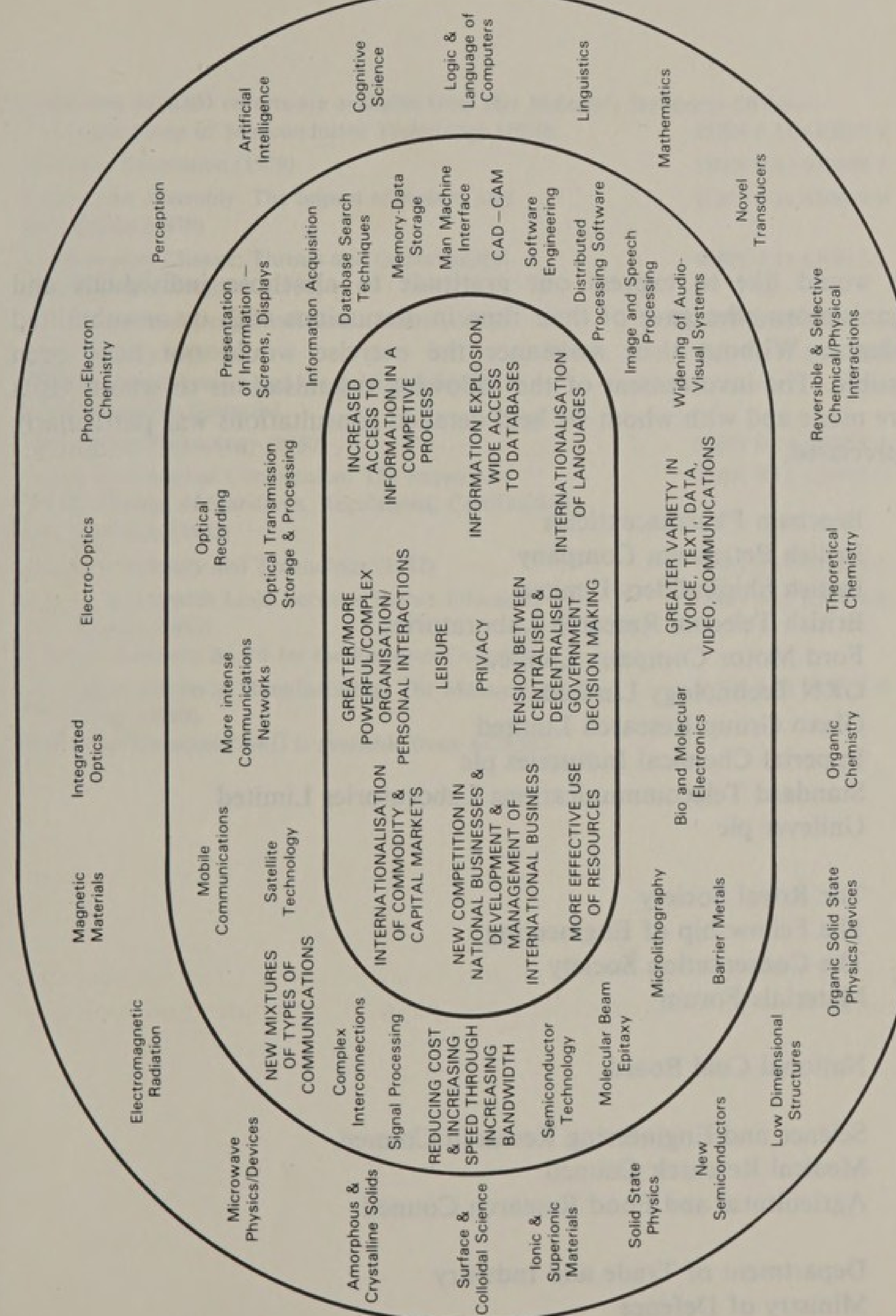
6.11.1. The earlier sections highlight those areas of core science which are likely to lead to developments in the acquisition and handling of information. By a similar token, progress will be required in key areas of mathematics so as to underpin the relevant science. Three important areas are summarised below:

Logic Theory This area used to be the purest of all subjects but, with the advent of high speed computing, this situation has altered dramatically. Indeed, the boundary between 'mathematical logic' and the 'theory of computation' is very indistinct.

Coding and Optimisation Theories Such theories are important for the construction of efficient algorithms in data processing and to overcome problems of computational complexity in the communications industry.

Artifical Intelligence Human intelligence is believed to be as much dependent on pattern recognition (a parallel processing activity) as a logical activity (a sequential process). Major developments are taking place in the sciences of artificial intelligence, a major thrust at present being in expert systems, computer programmes encapsulating human expertise in a form that can be interrogated. Such systems will have a role to play in capturing and transferring scientific knowledge (place to place or person to person) and in enhancing scientific creativity. Substantial progress in artificial intelligence may have to await the successful introduction of fifth generation computers.

6.11.2. In summary, there will be a continuing demand for mathematicians to develop theories which will ultimately enhance scientific creativity and improve technology. In many areas such as artificial intelligence and whole organism response, progress will only be achieved by close collaborative ventures between mathematicians and physical, computer and biological scientists.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INFORMATION EXPLOSION, WIDE ACCESS TO DATABASES
INTERNATIONALISATION OF LANGUAGES

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