SCIENCE RESEARCH POLICY IN SOUTH AFRICA

George F R Ellis

A DISCUSSION DOCUMENT

for the

Royal Society of South Africa

February 14, 2001

Preface

This science policy discussion document has been written by Prof G F R Ellis (University of Cape Town) on behalf of the Royal Society of South Africa, after a wide process of consultation within and outside the Society. While its circulation has been approved by the Council of the Royal Society in order to promote discussion of the themes discussed here, it should not be taken as reflecting the official views of the Society or its Council. Rather it should be seen as an instrument that can be used to promote public debate on the issues considered here, which we believe are of considerable importance.

The first aim is to work towards some kind of broad scientific consensus regarding the topics discussed here. For this reason there is included a substantial amount of explanatory material about each topic, that also acts as motivation for the research discussed in each area. The ultimate target is policy makers and influential public figures, who are usually not scientists. A much shorter version will be prepared for them, once the main document is satisfactorily revised.

The discussion here is quite detailed, as it has to be for this analysis to carry any weight. The last Chapter gives an executive summary of the conclusions arrived at in the main body of the document.

Undoubtedly the document has many deficiencies. We envisage that in due course, after further consultation and discussion, a revised and improved version may be issued. Comments and constructive suggestions on how to improve the content and the presentation will be welcomed. Please send them to:

Science Policy Consultation,
Royal Society, P D Hahn Building,
University of Cape Town,
Rondebosch 7700, RSA.

It would be most useful if such contributions, rather than simply giving general comments, would make specific suggestions as to how to alter specific sections or revise particular paragraphs.

Cape Town,
May 24th 1994.

* * *

Published by

Royal Society of South Africa,
P D Hahn Building,
University of Cape Town,
Rondebosch 7700, RSA.

ISBN Number 0-620-18564-3

* * *

Contents

Chapter 1

Introduction

Recently there has been much discussion of the future nature of science policy in South Africa ('SA'). Most of this discussion has focused on organisational issues on the one hand, and on the science-technology interface on the other. These are both of major importance, but the result is that by and large the discussion has not tackled specific issues that are of importance to scientists in their different areas of research.

A clear analysis is needed as to what is a sound research policy, taking into account on the one hand the country's direct needs (applied research issues) and on the other its long-term scientific and cultural development (fundamental research possibilities). This analysis should identify the areas where this country has particular needs and opportunities in terms of research, and the kinds of facilities and support required to allow high quality research in suitable areas.

1.1 A Consultation Process

A process of consultation has been initiated on this topic, based within the Fellowship of the Royal Society of South Africa but not confined to this body.

The immediate goal has been an initial overview of research opportunities and priorities as a whole, highlighting the various needs and opportunities in different areas. This discussion document provides such an overview as part of the process of consultation. It has been put together on the basis of comments received from many people (listed at the end) who responded to a request for views on the nature of future science policy, or gave comments on a first draft of the document.

It is envisaged it will be used to initiate discussion at a conference on the future of scientific research in this country, where scientists of different disciplines and other interested parties consider the major priorities in each area and consider how combined strategies and facilities can assist the different areas to interact in a cooperative and synergistic way.

This document is not a statement putting the position of the Royal Society or of its Council. Rather it is a discussion paper putting a particular viewpoint in order to provoke debate on important issues. Indeed it could be envisaged that it develop into a document that is regularly reviewed and updated on the basis of feedback and discussion between interested parties, through conferences, meetings, and discussions.

It has been commented that the document in its present form has something of a Western Cape bias. We accept that this is true. It has resulted from the fact that most of the responses received, on which the document is based, have come from the Western Cape. However to fully correct this would involve considerable extra time and effort; time pressure has led us to release the document as is. Hopefully this bias will be corrected in later versions as more comments are received and incorporated in the text.

1.2 The Theme of the Document

The theme of the document is priorities in the major 'hard science' research areas (it does not consider the social sciences). However, the discussion inevitably tails over to other areas, and indeed one of the specific issues to be addressed is the degree to which the different areas can be developed independently of each other. Proposals for research policy in particular areas have of necessity to be based on broad views of general science policy principles, strategies, and organisation. These are briefly discussed also. Given such broad principles, to establish science and technology policies one needs to consider more detailed

a) aims and objectives,
b) strategies,
c) themes and priorities.

These depend crucially on the context in which we are operating, and can be helpfully viewed in relation to the objectives and strategies of scientists elsewhere on the African continent. Within this broad framework, the aim is to characterise

(a) the kind of research work that could be usefully done in this country, both of a pure and an applied nature, in particular what fields can be particularly advantageously carried out here as opposed to elsewhere,

(b) the needed support for research - what facilities (equipment, computers), visitors, trips overseas, are needed for these fields, and what kind of organisation could make the latest technology, books and journals in the area available in this country with reasonable access guaranteed to all parties carrying out significant research work in the area (e.g. through centres dedicated to particular equipment and research areas),

(c) what provision should be made for central research facilities,

(d) what major projects could reasonably be supported as the 'big science' of a little country specifically, what is the case for the particle accelerator at Faure, the base in the Antarctic, and the possibility of a large telescope at Sutherland.

This paper gives a preliminary analysis of these issues.

1.3 The Subjects Discussed

The document has sections on the following areas:

A: Mathematical Sciences (1: Pure and Applied Mathematics, 2: Statistics, 3: Computer Science and Information Science).

B: Natural Sciences (4: Astronomy and Astrophysics, 5: Physics, 6: Chemistry, 7: Materials Science).

C: Life Sciences (8: Botany, 9: Zoology, 10: Microbiology, Biochemistry, and Biophysics, 11: Archaeology and Palaeoanthropology).

D: Earth Sciences (12: Geology, Geochemistry, and Geophysics, 13: Hydrology, 14: Marine and Atmospheric Sciences).

E: Environmental Sciences (15: Ecology, 16: Environmental Studies).

F: Interdisciplinary research. (17: Applied Science, 18: Community Science, 19: Human Ecology, 20: Human Development, 21: The Brain and Cognition, 22: Policy Research)

This leaves out specific discussion of:

(a) engineering and technology research,

(b) medicine,

(c) agriculture and forestry,

(d) the thorny issue of the social sciences.

In the areas of engineering and medical technology, a great deal of development is directed towards the application of emerging scientific concepts to national and international needs. It is not practicable to tackle this development work adequately in this document, and thus only occasional reference will be made to them. However, in our view, the same kind of overview papers should be prepared in these areas.

It must also be emphasised that within universities and research organisations there is a considerable amount of basic research carried out in engineering and medical departments, most commonly in areas which are needed to support development work and which are not well represented in science departments. These activities are referred to only peripherally in this paper, but represent an important thrust in the development of science and technology policy in that it is areas of basic research which support technological development which will increasingly become a focus in the future.

Several people have commented that one should approach science in a holistic rather than divisive way, and that the splitting up of subjects as listed above fosters division rather than unity. In principle we agree. However in practice, neither in teaching nor research can one tackle all things at once; it is necessary to split up the various topics for convenient discussion, as has been done here, and then to give precise definitions of what is included under each heading so as to avoid duplication of topics under various headings. The theme of how to promote a comprehensive approach to the various sciences will be picked up in the document and in its recommendations.

1.4 General Structure

Part I of the main document looks at general science policy principles, themes, and issues that are common to all the sciences; Part II at the specific sciences in turn; Part III at required support and possible priorities. The last chapter in Part III summarises the conclusions of the document. References are listed at the end, with a list of contributors.

An Index gives guidance as to where specific topics may be located [they may be referred to in several sections]. We recommend looking up subjects that interest you in the Index, to see the different contexts in which they are referred to.

Part I

CONSIDERATIONS ACROSS ALL SCIENCES

Chapter 2

Foundations and Context

The overall aim is to maintain an effective scientific research base in this country in the future, as this is important both from a developmental viewpoint, and in its own right (see e.g. Ellis, 1993). The issue is what should be the broad principles, aims, objectives, and strategies underlying science policy.

2.1 Foundations

Scientific research is one of the fundamental activities of humanity, and having an enquiring mind is what has enabled humankind to evolve to its present level of ability. To ask questions is to be human. Thus scientific research is not the prerogative of 'developed countries' nor of those states rich enough to afford it. It is as essential to being human as enjoying companionship or creating a work of art. It is important that countries create opportunities for fostering this positive aspect of human nature, and that role models exist to inspire youngsters to develop the enquiring minds on which civilisation is built (Bronowski 1976).

Indeed, knowledge and understanding are the basis of welfare; and the knowledge and understanding that underlie technology and medicine can only be attained by research. To a considerable extent we in this country will always be in the position of importing new understanding and technologies from other countries, however it is valuable and important to make our own contribution to such new knowledge where we are in a position to do so (cf. Ellis 1993). Furthermore, adapting imported technology to local conditions requires considerable understanding and experience of those conditions, which cannot be imported; it demands a local scientific expertise and research base.

In order to formulate a sensible research policy, input must come from a wide variety of sources, both within the science sector and outside it, through a suitable process of consultation. The need is a general science policy applicable in all sectors; but the results and implications depend heavily on the sector, so the specific nature and needs of the different sectors should also be considered carefully.

2.2 Context

The international and local context for such policy is rapidly changing.

2.2.1 Global: The Twenty-first Century

We need a policy that should be relevant well into the 21st century, accordingly it is important to consider how the 21st century will differ from previous centuries. In simple terms one might say that the 19th century was characterised by the opportunities offered by industrialisation, and the 20th century by the power of technology.

It is probable that the 21st century, dominated on the one hand by the problem of population growth and on the other by the new opportunities offered for instance by information technology and biotechnology, will above all be characterised by a realisation that the resources made available by the industrialisation and technology of the previous two centuries are limited. Indeed we have been living on our natural resource capital for the last two centuries, but it is no longer possible to do so (Brown, 1993, Flavin and Young 1993). The environmental impact of this profligate spending of non-renewable natural resources has included depletion of the ozone layer and the invisible threat of global warming (see e.g. Huntley *et al*, 1989).

The world has been shrinking with the increasing power of technology, and in the 21st century we will essentially be looking at a single global community, the 'global village'. Already we know instantly what is happening anywhere in the world, droughts in Somalia are seen in the living rooms in the USA, floods in Pakistan are seen by Peruvians. Economically the world is becoming more interlinked: we are all affected by the global economy. We also recognise global commons - the oceans and the atmosphere, and pollution by one or more nations can become a global affair (viz. ozone depletion). There is a growing awareness of the interconnectedness of everything, and that the natural resources of the earth are not limitless.

During the 20th century the development of the nuclear bomb had a major impact on humanity, with the realisation that a limited number of individuals had the power to destroy humanity and a substantial part of the biosphere. We are only just beginning to feel the impact of the realisation that humanity as a whole, by inappropriate misuse of natural resources, might unwittingly be changing the very life-sustaining nature of the planet. In the 19th century science was seen as a panacea for mankind, by the latter half of the 20th century scientists are seen as 'bad guys', the causers of pollution, the developers of the bomb. In the 21st century scientists should strive to lead the way in taking responsibility for husbanding the planet.

2.2.2 Developing Countries

According to the World Bank (Thulstrup, 1992), development is likely to be driven increasingly by research-based advances in science and technology (S&T), particularly biotechnology, new materials, information technology, and natural product chemistry, which are changing the nature of production and consumption. This will affect all developing countries, for four reasons:

1. New advanced technologies are often low cost, flexible, and dependable, and are creating new opportunities in developing countries. Some such as information technologies are already widely used in those countries.

2. The industrial applications of breakthroughs in basic scientific research are rapid and pervasive, for example the fast increase in the use of lasers, which leads both to completely new products, from CD players to surgical lasers, and affects manufacturing technologies. To adjust sufficiently fast to the changing technological opportunities, even developing countries must build up a minimum capacity in scientific and technological research and, particularly, research training. They must also create a system that ensures use of this capacity.

3. The mobility of capital has been increasing in recent years. The availability of a skilled labour force is a key factor in attracting external investments in high value added industries.

4. Environmental concerns are today of high relevance and have an increasing impact on the choice of economic growth strategies, not only

in the industrialised, but also in developing countries. Proper assessment and monitoring of environmental conditions requires scientific research experience and formulating and managing national environmental policies requires a considerable amount of well trained S&T manpower.

It is thus vital to aim at production of S&T graduates, but this will only be effective if the education is of good quality and relevant to national needs, with research investments part of a consistent national science policy.

2.2.3 Africa

Africa as a whole is subject to poverty and underdevelopment. Related to this is an underdevelopment in the area of science and technology. The African Academy of Sciences has considered identification of scientific research required to contribute to solutions of African problems, and those areas in which a potent African capability needs to be strengthened to enable African scientists to work productively on a sustained basis (Odhiambo and Isoun 1989). They state,

> African Governments and their societies unanimously support the global objectives of rapid industrialisation and technology development geared towards increasing national productive output and developing dynamic and self-reliant economies. There are however ineffective mechanisms to realise these objectives, as evidenced by the minimal investment made by African nations (0.1 to 0.15% GNP) on research and development (R&D) and for the training of skilled human resources to sustain scientific creativity and technological innovation.

The situation of science in four African countries (Tanzania, Zambia, Uganda and Ethiopia) was investigated during a trip on behalf of ICTP in 1988 by E Lillethun. The main difficulties in all four countries concern scientific manpower, level of physics and maths education, and equipment. Specifically,

* physics is taught theoretically, like history, in the secondary schools, without student experiments or even demonstration experiments;
* students entering university are greatly deficient in knowledge of physics and mathematics;
* existing student laboratory equipment is old, missing, or not working, in undergraduate studies as well as in secondary schools;
* the recruitment of mathematics and physics teachers is far too low;

* university science lecturers are overloaded with work, in particular with teaching first-year students who have to study some basic mathematics and physics in order to be admitted to other studies like medicine, agriculture, education, etc.

* the salaries of teachers and university lecturers is so low that they are forced to take on other employment to make ends meet.

Certain initiatives are being taken to break this vicious cycle. Work is in progress to supply secondary schools with scientific equipment, preferably made locally. Crash courses are planned for science teachers. There are plans for science fairs and competitions to attract young people to scientific and technical careers. All this requires extra manpower, extra specialists and extra funds. It is also clearly seen that this requires collaboration, both regionally and with industrialised countries.

2.2.4 South Africa

The South Africa ('SA') of the 21st century will be part of the global community. It will increasingly be affected by what happens in the rest of the world, and in Africa. It is unlikely to become a 'great power' during the next century because of limited human and natural resources. It must accept this and find an appropriate niche where its resources can be maximised through cooperation. In comparison with the rest of Africa it has a head start in terms of skills, infrastructure and potential, which should be developed to take advantage of SA's position in the continent and in the relatively undeveloped Southern Hemisphere. However it will also have major and urgent concerns to be dealt with in terms of health and welfare, housing, education, transport, and food production, and corresponding demands that public expenditure, including that on science research, produce more or less immediate benefit.

In order to tackle these issues effectively, the future workforce in SA must be given a solid grounding in science and technology, and for this to occur we need scientists and engineers of a high standard to act as teachers and mentors. This cannot take place without the necessary scientific infrastructure of university and other research programmes to encourage, maintain and retain people with scientific vision and drive. We are in the very fortunate position that we already have a large part of the required infrastructure in place, although so far it has not been functioning effectively to address the socio-economic problems of the majority of the population.

Indeed, SA is in the relatively rare position of having a large Third

World community with its attendant urgent problems of health, housing, nutrition, education, and employment, together with a strong First World community of scientists who could address many of these problems in their research. Furthermore it is clear that in Africa south of the Sahara, the level of research expertise required to effectively address most environmental problems, particularly in the field of marine and atmospheric sciences, is presently to be found only in SA. It is not envisaged that this will alter soon. These circumstances place a great responsibility on SA science, but also open up a large number of exciting opportunities for cooperation, support, and relevant research in SA and in Africa.

A considerable problem is seen in the way that science research in SA in the past, with its distinguished tradition (Brown 1977), has been aimed very largely at academic issues – extending the frontiers of knowledge – and only to a limited extent addressing the problems of society; and insofar as it has done that, in the main it has aimed at improving the quality of life of the privileged rather than uplifting the situation of the underprivileged.

In view of the failure of science (and indeed the whole socio-economic-political system) to address successfully the needs of the majority, there will be considerable pressure to place science directly under political control aimed at redirecting its efforts and output towards meeting these needs.

However any national science policy needs to take clear cognisance of the ethos and culture of scientists, in order to retain the best intellectual talent of the country and to foster mutually beneficial cooperation and collaboration with developed countries. The most talented and productive scientists naturally gravitate towards centres of excellence where they can do the best research. Good research flourishes only where a culture of free enquiry is generated and where intellectual stimulation is encouraged. An effective national science policy will therefore have to be so constructed that it will make it worthwhile, stimulating and challenging for top scientists to work here - in particular providing opportunities for them to do so in those research areas that will be of most short- and long-term benefit to the peoples of Southern Africa.

The effectiveness of science and technology (S&T) policy will depend on large-scale education in science, engineering, and technology. However the situation in science education is made difficult by the very low quality of much school level education, as a legacy of the Bantu Education era; this is presently strongly restricting the supply of students suitably qualified to enter university or technikon science and engineering degrees.

Chapter 3

Principles and Guidelines

These global, international, and local situations present a range of demanding challenges to future SA science policy and science management. With significantly more South Africans represented in the Government, national policy will direct more resources to meeting the basic needs of the poor majority. However this emphasis will have to be balanced against the need to ensure industrial and economic competitiveness and also environmental sustainability; in broad terms, investment in the future developmental capability and sustainability of the economy.

It seems broadly accepted that technological developments in SA in the future will need to address two distinct areas. The first is maintenance, or indeed the establishment, of South Africa as an internationally competitive manufacturer and supplier of goods and services. The second is the application of technology to improve the living standards, health, welfare, and opportunities of that sector of the population which has been disadvantaged throughout the Apartheid era. Both these aims in turn demand firstly suitable research into the relevant areas, and secondly developing managerial, economic, scientific, and technological abilities so that all the people of this country can utilise their inherent skills to best advantage.

3.1 Principles

In considering science policy, it is first of all essential to consider the basic developmental needs of our society, focused on the triad of employment - health - education. Some scientific research can be directly aimed at these issues. However research should not be limited to these areas, for a strong scientific community and understanding is an essential pre-requisite for the wise management of the country's resources and environments; indeed one can claim that irrespective of the political dispensation in the country, fundamental quality of life attributes such as food, health and shelter can only be improved with a solid underpinning of scientific research.

The issue is what is the best direction of that effort. In view of major resource shortages, in broad terms scientific research in South Africa must be directed towards *attacking problems, gaining knowledge, and building skills which will be of lasting benefit to SA*. This does not however restrict scientific research to that immediately relevant to social or developmental issues. A strong foundation in fundamental science is needed both for high level training and for essential applications in the fields of industry, agriculture, environment, and health, and for technology evaluation; research activities are essential for the creation of such a base and for keeping it up to date (Thulstrup 1992). Thus we must emphasize the extensive links which it is necessary to establish between fundamental research and ultimate benefits, in particular the need for greater integration of science and engineering into society, and for development of scientific and technical education that can help make a reality of those links.

The objectives and rationale of scientific research should be formulated in these terms so that the ultimate objective is abundantly clear to scientists, funders, and beneficiaries alike. In this way the priority of research can be assessed and the results weighed.

Thus our research programmes must be relevant to South Africa's needs and priorities for the medium and long term. But relevance does not mean discarding important basic studies in preference for short-term priorities. It means dispelling the myth that 'blue sky' research is the only route to discovery, and that good science and problem-oriented research are mutually exclusive. However it also means recognising the crucial role of the ethos of fundamental, basic science in marketable product development, and that real freedom of inquiry requires researchers to ignore commercial considerations at the outset and explore ideas that provoke their curiosity [Lutjeharms and Thomson 1993].

To summarize, the aim should be

1. So to fund and structure science that research in SA is to the ultimate benefit and lasting advantage of its society.

Such a policy should however

2. Affirm that scientific enquiry is an essential part of being human (and not merely the handmaiden of technology), encouraging understanding for its own sake, and also the sense of responsibility that comes with knowledge;

3. Take cognisance of SA being increasingly part of an ever-shrinking world, encouraging advances which enable humanity to live in sustainable harmony on the planet.

3.2 Guidelines

First, *Relevance*: Research must be relevant in the sense just defined. A proper balance must exist between highly directed and goal oriented work which is a pre-requisite for day to day resource management or solving immediate practical problems, and free-thinking process-related studies and research which are at the cutting edge of science internationally, and often form the basis of long-term strategies towards the problems facing us. We should not support research for the sake of gaining new knowledge without any practical applications in sight, unless there is a strong case for it in terms of opportunities presented, understanding gained, or contribution to the local scientific infrastructure.

Second, *Quality*: Scientific research is not worth doing if it is aimed wrongly or not done properly. Fundamental scientific qualities must be present not only for basic but also applied research. There are three aspects to this. The first level is competence: environmental monitoring, medical laboratory tests, or product development will be worthless if measurements are not performed properly, data treated correctly, and conclusions drawn in a logical way (Thulstrup 1993). Only if the quality of this (first) level is satisfactory will the social, economic, scientific, or educational relevance of the results (quality on the second level) be of any significance. This is where the issue of research priorities is important. The third level is the question of originality of approach and results. The rare quality is the ability to see things in a new way or introduce new methods, opening up new approaches; that is where the really major contributions are made (in 'pure' or applied fields).

Academic standards within the universities and technikons at all three levels must be maintained if we are to compete in a world dominated by international trade in commodities, knowledge, and human resources. Thus all scientific activity, whether in research or in implementation, needs appropriate quality controls. But peer review must not be limited to one's colleagues within a scientific discipline; it needs to involve cross-disciplinary comparisons, despite the difficulties in making such comparisons.

Third, *Preserving and Exploiting Current Expertise*: We need to preserve and exploit our existing strengths. For example, Zoological Research and Biomedical Research in SA are rated amongst the top ten in the world (Pouris 1989). We need to understand why this is (are our scientists in these disciplines more efficient, more productive, etc.? Do zoologists attract more international celebrities to work here because of our indigenous fauna?), so that we can aim to maintain our position of strength in these areas, and perhaps transfer this understanding to other disciplines.

Fourthly, given our historical situation, there should be a strand in our science policy of *action to redress inequalities.* There are major sectors of our communities who have been largely left out of the advances of scientific knowledge and technological benefit, and whose members have hardly entered the scientific and technological arenas. Thus we need to aim to address the racial and gender bias inherited by the scientific community, in a sensible manner, that is in a way that makes positive advances in these areas but does not stifle or nullify the rest of the enterprise.

3.3 Broad Objectives

Our objectives in developing science for a better SA, directed towards the common good, should be to undertake:

1: Research activities directed towards improving the well-being of people and their environment, contributing significantly to the knowledge, understanding, and actions necessary to attain an improved, equitable, economically and ecologically sustainable quality of life for all our people. This involves high-tech research for high-tech industries of the kind pursued by CSIR and MINTEK; low-tech research in applications for low-tech industries; and developmental work for community benefit, together with environmental research for the long term continuation of the needed foundations.

2: Research activities directed towards fundamental understanding where it is inexpensive and productive in competitive international terms, and towards activities of a more applied kind, with an emphasis on long term returns as well as short term gains. There is a particular case here for continuing work of quality that is already being undertaken by existing research groups in the country.

3: Activities directed towards building up scientific and research ability in the future, in particular developing expertise in relevant scientific and technical areas and improving scientific education, as well as activities aimed at increasing public enthusiasm for and understanding of science.

4: Activities directed towards clarifying the tradeoffs that have to be made as we plan our future. Development cannot be entirely free of environmental cost, for the key determinants of human well-being - economic growth, environmental health, and quality of life - cannot be maximised equally and simultaneously. Trade-offs have to be made, so we need clear understanding of what the choices and options are.

In brief, we should carry out both applied and pure research in an effective way. This demands *research capacity development*:

5: A cooperative process of planning leading to a common purpose, vision, and mission, and to detailed planning, as a participative process between the scientific community and the public at large. This two-way consultation process needs to be tied in both to the strategic planning process mentioned in the next paragraph, and effective funding mechanisms that can make a reality of the conclusions reached.

6: A strategic element in the planning process that examines our research needs, strengths, and weaknesses, establish needs and priorities as well as identifying major gaps in our current research programmes and in needed support infrastructure (personnel, equipment, books, institutions). We need to develop strategic plans for each area, and for science as a whole. There should be a process that can define research gaps and ensure that they are filled. Strong fields are becoming stronger, but some fields are being neglected completely.

7: Promotion of coordination, communication, and cooperation between researchers in the same field, and also in different fields, because knowledge gained in one field may well help solve a problem in another field. This should be done both in SA and internationally. There is a need for a cooperative culture emphasizing communal problem-solving.

These general aims are broadly compatible with those of the African

Academy of Sciences (AAS), whose objectives are characterised as follows (Odhiambo and Isoun 1989):

1: To promote and foster the growth of the scientific community in Africa, and to stimulate and nurture the spirit of scientific discovery and technological innovation in order to serve socio-economic development and regional integration and to serve the cause of global peace and security.

2: To stimulate, design, and coordinate regional inter-disciplinary scientific research development and demonstration projects, or activities of major regional interest and concern.

3: To plan, convene, and coordinate science education programmes of crucial importance to Africa as a whole.

4: To help in developing and nurturing high-level scientific and technological manpower in Africa by identifying talented young scientists and technologists through recognition of their merit, and by promoting the growth of their creativity.

5: To facilitate, coordinate, and undertake the publication of science progress in various media, to foster dissemination of scientific knowledge throughout the continent, and to facilitate mutual contacts between scientists in Africa.

Chapter 4

Science Policy Themes

These general principles become meaningful and purposive when tied in to the particular themes that are likely to structure and dominate research needs. We consider these in the world context, the broad African context, and the local SA context.

4.1 Important Areas: World

The global transformation to an information-based economy, and the new opportunities offered by biotechnology, have been widely remarked on. The further important theme of altering to a sustainable basis the way we approach resource use, is at its initial stages, but will become of major importance in the relatively near future (Brown, 1993). As stated by Flavin and Young (1993, p.180),

> 'The need to achieve an environmentally sustainable world is now shaping the evolution of the global economy. During the nineties, ecological pressures will increasingly influence economic decisions, making some industries obsolete while opening up a host of new investment opportunities. Companies and nations that fail to invest strategically in the new technologies, products, and processes will fall behind economically - and will miss out on the new jobs that these industries will provide'.

The kinds of research needs seen for an advanced industrial nation may be noted in the choices of Dr. Alan Bromley, Science Adviser to President Bush, who was responsible for selection of the following topics as major presidential scientific initiatives:

* global change research
* high performance computing and communications
* material science and processing
* advanced manufacturing
* biotechnology
* mathematics and science education.

These topics were selected after careful study as being of leading importance for the USA.

4.2 Important Areas: Africa

The African Academy of Science (AAS) consultation (Odhiambo and Isoun 1989) focused its attention on three major themes.

Theme One: Creating an enabling environment for R&D focused on African development on a sustainable basis.

The theme was developed in some detail; in brief outline,

1. The Association of African Universities (AAU) should play a leading role in evolving new approaches to S&T which emphasize practical involvement of university faculty and students with:

* agriculture in support of food production
* local industries and occupations; and
* local entrepreneurs including the informal sector.

2. Training at university level should be designed to incorporate into the scientific and engineering programmes, courses that cater for the entrepreneurial development of future generations. The courses should be modified to include courses in management, politics and economics.

3. The AAU should endeavour to change the evaluation and reward system of university staff to encourage cooperation with the informal sector as well as with agro-industries and the industrial sector.

4. There should be close collaboration between universities, research institutes, and national planning agencies; this collaboration should emphasize R&D geared towards socio-economic goals which are target oriented. Furthermore, technological triangles should be established as a means of

converting knowledge into wealth for the improvement of the human condition.

Theme Two: Evolving mechanisms for creating an interface between science, industry, and government.

5. Information data base: The AAS should examine the existing national and regional information initiatives, and sources from outside Africa, for the establishment of databases for possibilities of networking. The information data base should be created for use by scientists/engineers, industrialists, and policy makers. The services of the data base should be commercialised and paid for by users. The services provided by the data base should cover technological research findings, possible applications of existing technologies, products of technological innovation, and textbooks.

6. Teaching materials: The AAS should organise a programme to promote the publication, popularisation and distribution of technical books to facilitate the extension of S&T to the general public.

7. Sensitization of institutes of technology: University and research institutions should play a promotional role in the development and growth of small-scale industrial operations. They should initiate and operate industrial consultancies. They should model themselves to provide service on the basis of their expertise to the government and industry as a source of income.

8. Scientists as entrepreneurs: Individual scientists should be encouraged to go into industry. They should start small-scale industries initially but with the vision of developing their businesses to large-scale economic levels.

Theme Three: Financing of R&D in both private and public sectors.

9. The African Development Bank (ADB) should be involved as a partner in this enterprise of initiating and promoting R&D.

10. There is an urgent need for industry and the private sector to get involved in financing R&D enterprises. In this respect Governments have a critical role to play in establishing incentives, such as tax-exempt contributions by industry to R&D that would promote and bring about development of industry.

11. The Future Actions Committee should appoint specialised task forces to identify critical scientific problems areas with potential R&D benefits to the African continent. The task force should be responsible for developing plans for their implementation.

The AAS set the following specific objectives, to be met by the year 2000:

* self-sufficiency in basic food production for Africa.
* self-reliance in transportation and basic equipment for land and for inland waterways and agriculture.
* self-reliance in production of basic educational materials and equipment.
* self-reliance in energy supply, particularly intra-continental gridding of hydro electricity and distribution of fossil fuels.
* production of 50% of drugs and medicaments required in Africa.
* entrepreneurs to (a) reinvest or give grants of not less than 10% of their profits to research and development and (b) make scientists their close allies in indigenising their production and products. Investment or grants to research and development should be made tax deductible by governments.

The Lillethun investigation of scientific conditions in Africa noted that research is primarily aimed at fields relevant to applications for the development of countries. In physics this means experimental research in fields like

- radiation physics, with applications in medicine, agriculture, etc.
- alternative energy sources, i.e. thermal, photovoltaic, biomass, etc.
- materials science, for study of local materials, solar cells, etc.

With the existing financial and manpower limitations, it is realised that research can be carried out in each institution in only one or two specialised fields. Research is more hampered by lack of manpower and consumables than equipment. If research is to be carried out in additional scientific areas, collaboration with research teams on a wider scale will be absolutely vital. Much can be achieved through regional collaboration. However North-South collaboration can speed up the process. Particular priorities are:

* Instrumentation for use in industry, medicine and other sciences. This is an important research and development field, to be promoted by the International Centre of Low Cost Scientific Equipment.
* To set up an organisation to develop and produce laboratory equipment for secondary schools.

* To investigate the potential of microcomputers in science education.

4.3 Important Areas: South Africa

The themes from Africa are largely those relevant to SA too (cf. Ellis 1993). We have immediate problems and research needs in the areas of

* water supply
* agriculture and food supply: fish, animals, birds, plants
* energy supply, storage, use, conservation
* mineral resources: location, extraction, processing
* work: processing, manufacture, services
* environmental assessment, processes, restoration
* pollution, waste disposal, sanitation
* transport: energy use, efficiency, cost
* health: preventative care, curative
* education
* information technology
* planning, optimal use of resources

These lead to a host of research needs of an applied kind, similar to those experienced in the rest of Africa and identified by the AAS (1989), for example

- better management of water resources; irrigation projects, water harvesting systems, forecasts of drought;
- gene banks: comprehensive collection of crop, tree and animal germplasm;
- better understanding of the structure, fertility and management of tropical African soils to upgrade conservation and management, and control of soil erosion by wind and water;
- household food production and food security;
- afforestation and agroforestry projects;
- post-harvesting and processing technology;
- insect control to protect plants, domestic animals, and the human population;
- the need for better mathematics and science education in SA is widely recognised. Some of the problems here may well be partially solved by remote teaching using electronic devices powered by solar energy;
- the major need in SA is for labour-intensive rather than capital intensive industries. However that use of labour may well in many cases be

made much more effective by appropriate technology methods, e.g. in food processing and packaging;

- more beneficiation of materials before export.

Additionally we are at least potentially faced with the high-tech problems and challenges facing more advanced societies, such as those listed by Dr. Bromley (see above). The question here is which of those we can suitably invest effort in. Overall an important theme is that of the scientist as entrepreneur. Crucial elements are networking of development, supply and demand, and a focus on appropriate technology.

Clearly global warming and the associated advance of the deserts is of particular concern to SA, and we are well placed to carry out research in these areas. Similarly if biotechnology can lead to the introduction of drought-resistant metabolic pathways into crop plants, it will be of great importance to SA; and this is an area where we could reasonably hope to make serious contributions, if suitable personnel were to be employed.

We are well placed to make contributions to science education for disadvantaged students, and indeed are already in some cases doing well in this area by international standards. While SA must be ready to use high-performance computing and communications in mass education, the idea that SA could compete with the USA or Japan in developing the hardware of the future is not to be taken seriously; however it could possibly make useful contributions in software. Similarly SA cannot hope in the near future to compete with current leaders in the general field of advanced manufacturing, though isolated applications (e.g. the assembly of electronic teaching devices and measuring instruments, other educational toys, books, and aids, or the design and manufacture of wind surfers and paragliders) could be appropriate. We could contribute here to the global trend towards more ecologically sound economic activity and resource use, based on better understanding of environmental processes and design and manufacturing possibilities. The remaining field identified by Dr. Bromley, materials science and processing, is one where SA is better placed than many countries to make major contributions.

The above discussion provides a broad set of themes that are of importance in research in the future. However some other specific themes stand out as worth specific mention.

4.4 Cross-disciplinary Interaction

Many of the topics already mentioned can only be properly addressed in the context of a cooperative and inter-disciplinary approach that is perhaps rather rare at present. This is evident for example in looking at

a: agricultural and technological development: how could one increase the contribution of scientific research to agricultural and technological development, and foster cooperation and resource-sharing between the academic, industrial and agricultural sectors?

As in other developing countries, interdisciplinary work between biology and chemistry may be very promising here (Thulstrup 1993), because of our comparative advantages in terms of particular raw natural products.

b: the role of physics, chemistry, biochemistry, molecular biology in medicine, where South Africa is in a very good position.

However there is a need also for promotion of other specific inter-disciplinary research areas of importance, such as

c: The effect of human population growth

d: Science policy research

e: Science education research

f: Science philosophy and its relation to culture

[These will be discussed in more detail later].

There is a trend world-wide for some of the best research to be done by relatively small specialised units that collaborate with other small specialised units to form multidisciplinary teams. Such teams remain flexible, competitive, and innovative, and do not become overburdened with bureaucracy. In line with this, the aim in each case should be to coalesce inter-disciplinary research groups around application areas, e.g. the marine and atmospheric sciences, or agricultural issues.

To make this effective, a cross-webbing structure is needed: experts in basic disciplines (maths, statistics, physics, chemistry) can be brought into teams to tackle each of the application areas listed above (energy, agriculture, etc.), undertaking integrative analysis in collaboration with workers thoroughly familiar with those particular areas and with experience of developmental problems and the requisite expertise in social sciences (developmental economics and sociology, for example).

We should note here that one person's application is another persons 'pure' science (for example applied mathematics is one strand in developing solid state physics, a subject in its own right; this is one strand in materials science, which in turn is a basis for many applications in technology). There is a need for teams targeted at different stages of the application of science to practical problems, forming an overall network that ends up with applied teams tackling community developmental, environmental, and economic problems.

4.5 International Cooperation

Many of the activities we should be involved in can only be successfully undertaken through active involvement in international programmes such as those of SCOPE, IUBS, IUCN, or cooperation with workers in the major world scientific centres, both on an individual basis and through international organisations such as those adhering to ICSU (see FRD:ICSU and ICSU 1993).

Compared with the rest of Southern and Central Africa, SA has a strong research base in a wide variety of fields of science and applied science. Much of our expertise could be used to assist other African states. Conversely there are interesting research projects to be found in neighbouring states, and experienced workers there who could help us with projects here, particularly of an agricultural and biological nature, We should strive to open that door widely and encourage a strong flow of ideas and people involved in research between SA and the rest of Africa, particularly southern and central Africa. We should set up connections with scientific bodies in the rest of Africa (as advocated by the AAS). Such interaction will be mutually beneficial, and should form a major part of future scientific planning. It will enable us to take part in and contribute to an increasing trend to such international cooperation in science and technology, with a particular focus on developing countries (Carnegie 1993, Carter Centre 1993).

4.6 Science Education

Major challenges are to bridge the gap between the inadequate schooling provided to many South Africans and the demands of a modern university curriculum, and to provide a modicum of scientific and technical ability to those who have more or less completely missed out on their schooling. The first issue is being dealt with, with some success, through various Academic Support Programmes. The second has hardly begun to be tackled.

The problems of this kind facing us require a team approach and development of cooperative ventures, linking the activities of the best scientists, managers and administrators, educators, and communicators, with members of the community. There is a need for a wide range of classes, symposia, workshops, TV/radio/video programmes, and field activities that can provide an informal entry point for many disadvantaged people into SA science. There is considerable scope here for methods whereby any interested party, regardless of academic or professional status, could participate in advancing science through cooperative efforts such as the Protea Atlas Project, Bird Atlas Project, weather observation, and environmental monitoring efforts. The point is that projects of this kind can enable amateurs to make a real contribution to research in some areas: astronomy, botany, archaeology to name a few. Thus they help build up and create an informed, intelligent lay public with an interest in and commitment to science. A particular effort could be devoted to setting up such projects that schools can participate in e.g. taking systematic weather observations. Participating schools in such a project would send measured information in to a central data bank; in return, they would get output from it, e.g. computer/video information on weather patterns and correlations determined from the data. They might be challenged and encouraged to develop weather forecasts of their own.

Solution of the educational problems facing us requires research on learning and teaching methods, in particular in remedial programs. These are areas where developments in the area of cognitive sciences are showing promise of helping make substantial improvements. Thus it is important to develop research in science education (Grayson 1991), including in particular research into learning and teaching in the critical area of mathematics - the primary stumbling block to entry into serious science studies.

An important point here is the need to emphasize learning to think about scientific matters as against rote-dominated teaching. Biology particularly suffers from this, for its abundance of factual material is a soft target for rote-trained teachers who lack the skills and support for getting pupils to think for themselves. The specific techniques for teaching thinking skills need to be made central to science education.

Two subsidiary issues of importance arise here. The first is that while science studies can to some extent be done in the vernacular languages, serious study must inevitably be done in one of the major world languages; and English is without any question now the language in the ascendance in world science, and is the language in which higher level science should be taught. Thus a major problem arises in that the majority of people in this country will have to do much of their science studying in a foreign language - a far larger stumbling block than many realise. This means it is fundamentally important to consider learning and teaching issues arising from the use of English as a second language in science studies. This is thus one of the areas where significant research on learning difficulties, and ways to overcome them, needs to be done.

The second is the optimal syllabus choice, which also needs careful investigation; it can make all the difference to the overall quality of scientific education and the subsequent attitude to science of school leavers. Here it is essential to realise that it is often not so much the syllabus itself, but rather the emphasis on exams, and particularly the kinds of matric exams set, that is the biggest problem. The exams in fact define the nature of the real syllabus, in that they shape a great deal of the way the subject is approached and taught; and the exam-oriented way of teaching makes the subject excruciatingly boring. Thus a key issue is the nature of creative assessment and examination methods.

Again a particularly important issue is the question of the school mathematics syllabus and examinations. It is therefore important to study ways that this syllabus can be made more meaningful to the majority of pupils, and related strongly to creative educational methods (Ellis 1993b).

At the tertiary level, apart from imparting basic knowledge and skills, the essential concern is training in scientific research methods. 'Quality in university research and research training is important for industry, not only in connection with development of new technologies or the creation of scientific and technological breakthroughs, but to an even larger degree for providing a basis for the efficient and innovative use of up to date technologies' (Thulstrup 1993). Thus the requirement is for active research schools that provide training in research methods at a high level (these have many other benefits, see Thulstrup 1993).

4.7 Scientific Support Programmes

The future of science in this country will depend on the perception that prospective scientists receive from their family environment, school, university, government, and industry. To create an enlightened and positive attitude towards science and its benefits to the country as a whole, popularisation of science must be given priority among the population in general and among secondary school pupils in particular. Science policy should aim at the popularisation of science in a businesslike, targeted manner, with clear goals and objectives.

The challenge is to develop an appreciation of science in the general public. This has hardly begun to be tackled, except at some museums and to an increasing extent on television (but largely imported, and thus able to make only a limited impact on local culture).

This is part of the broad project of encouraging a science culture in the population at large. In the future SA society we need to stress the roles of both applied and basic research in everyday life (for example in terms of the practice and foundations of medicine). There is a universal trend away from pure science, even in first world countries such as the United States. The reason is the public's perception that basic science is not fun, is not appreciated, and leads nowhere. These issues need to be addressed at a popular level. It is significant that in those cultures where science flourishes, e.g. Israel and Italy, there is a basic public appreciation for the intellectual aspects of science. There can be no doubt that a healthy thriving economy will lean heavily on basic science as well as applied science and technology. Promising school leavers and university graduates need to be encouraged to enter science. In Spain there is a specific programme which popularises the achievements of Spanish scientists in the international sphere. The American Chemical Society has a well-supported programme to explain the role and functional possibilities of chemistry, by members addressing schools, parents, teachers conferences, and by literature and brochures, which explain what a chemist is. They also produce well-thought out video tapes, which are available for home use. There is a need for similar projects in this country. In this country it is encouraging that the National facilities (NAC, SAAO, HartRao) have for many years had active programmes to popularise science, especially amongst high school students.

4.8 General Science Policy: Organisation

Broad goals for a science policy of the future are suggested above, and more detailed proposals are given in Part II. In order that they could be implemented, they would have to be debated in some suitable consultative process, in competition with other proposals that might be put forward, and some suitably modified version agreed on. Given such agreement, a host of organisational issues then arise, for example, by what mechanism should we establish priorities and allocate funds, and how would the needed research effort be supported?

These and other organisational issues have been the topic of many other discussions, for example IDRC (1993), Whiston (1993). Some of the major issues arising are mentioned in Part III of this document.

Part II

SCIENCE RESEARCH POLICY (SPECIFIC SECTORS)

In this part, we consider separately the various areas of science, and put forward a view on research needs and priorities in each. We consider in turn, A: Mathematical Sciences; B: Natural Sciences; C: Life Sciences: D: Earth Sciences; E: Environmental Sciences; F: Interdisciplinary Studies.

One should note here that even the choice of topic areas and associated classification of subjects is a statement of priorities, and could have been done in many other ways (for example, is palaeontology a subject in its own right, or an area of specialisation of geology or of zoology?). A particular classification has been chosen which seems to be coherent and make sense. It starts with specialist topics and moves to generalised studies, the more basic topics discussed earlier forming the foundations for the more applied areas considered later.

It is helpful to make a distinction between two kinds of interdisciplinary studies. We will label as *Integrated Sciences*, those studies such as ecology that involve simultaneously various branches of the 'hard sciences'. They are 'interdisciplinary' in the restricted sense of not being confined to a single basic science subject, such as chemistry or physics. In contrast, *Interdisciplinary Studies* will refer to subjects that involve also subjects other than the 'hard sciences' - some of the social sciences or other branches of learning. For example, environmental studies necessarily involves economics and law as well as ecology; if studied in depth, it also has elements of psychology, sociology and politics. In terms of these definitions, both medicine and engineering are interdisciplinary studies (even if not always taught that way).

The feature to emphasize then is that the classification used here carefully distinguishes these two kinds of subjects. All the important applied research takes place in the context of interdisciplinary studies, as defined above; they necessarily involve social science areas that are difficult and controversial. However from the viewpoint of science research, it is important to separate out those scientific issues that do not involve these kinds of topics, and so are free from these controversies. In terms of our definitions, these are the basic and the integrated sciences. The findings of these sciences are the foundations for interdisciplinary studies, but are not affected for example by the viewpoint taken on economic issues (which are important in interdisciplinary studies).

In terms of these definitions, the move underlying our classification scheme is *from basic to integrated to interdisciplinary studies.* By and large the later subjects are closer to application.

A: Mathematical Sciences

The mathematical sciences underlie all the other hard sciences because the power of modern science is based on the use of mathematical models of real-world systems. In particular, the laws of physics and physical chemistry that describe the behaviour of matter are expressed in mathematical terms, all experimental work depends on statistical analysis of observations, and the operation of digital computers is based on the laws of logic as expressed in Boolean algebra.

The topics considered in this section are, 1: Mathematics (Pure and Applied); 2: Statistics; and 3: Computer Science, together with the integrated subject of Information Technology.

Chapter 5

Pure and Applied Mathematics

Mathematics is the systematic study of quantitative relationships. It is the foundation of all other quantitative sciences and applications in technology, being particularly central in physics and chemistry, but also to an ever-increasing extent in computer science, biology, ecology, medicine, and environmental science.

The major division has been between pure and applied mathematics. Within *pure mathematics* some of the major branches are geometry and topology, analysis, algebra, combinatorics, number theory, mathematical logic, and foundations of mathematics. Within *applied mathematics* some of the main areas of activity are mechanics, theoretical physics, theoretical biology, and numerical analysis. Differential equations and, more generally, dynamical systems and the related areas of fractals and chaos, are some of the areas which straddle the pure/applied divide.

5.1 The Nature of Mathematics

Pure mathematics focuses on generalisation and abstraction; so the link with applications can be quite distant. However, a recurring theme is that what at first might seem to be abstract work with no practical use later turns out to be central to major practical developments (examples being the role of group theory in modern theoretical physics, the use of functional analysis in numerical methods, and the use of number theory in coding). It is therefore unwise to assume that any branch of pure mathematics, no matter how abstruse it seems, will never find significant practical application.

Nevertheless the driving force behind pure mathematics is the understanding of patterns and relationships for their own sake, as opposed to applied mathematics where the essential theme is the construction of simplified but reliable quantitative models of the system under investigation (Ellis 1974, National Academy 1984). This has reached an advanced stage in many cases (as codified for example in many engineering and medical applications), but is still often elusive.

In both areas, perhaps the most interesting and significant aspect is the aim of unification of previously separate, widely different aspects of the subject (Steen 1980, Davis and Hersh 1981, Stewart 1987). One way in which this is apparent is the procedure of generalisation and abstraction that has driven so much mathematics, e.g. in the definition and investigation of geometry, calculus, groups, and categories. The other is the most exciting aspect: where previously unsuspected unities and connections suddenly become apparent, as in the recent claimed proof of Fermat's Last Theorem by Wiles. This is part of an interesting new drive towards unification in pure mathematics, after a period of dispersal and somewhat unrelated activity.

In recent years a new vigour has been apparent in many branches of mathematics, due to the availability of modern computers. This has been apparent in the rise of computational mathematics, discussed in some detail below, and in the discovery of quite unexpected phenomena hidden in simple mathematical equations, now formalised in the study of fractals and chaos theory. Attempts to construct a satisfactory mathematical theory of complexity are still in their infancy.

5.2 Present Strengths

According to Grobler (1992), SA mathematical research is presently strong in the areas of

* categorical topology
* categorical algebra and algebraic topology
* number theory
* ring and near ring theory
* graph theory
* functional analysis and operator theory
* ordinary differential equations,

* partial differential equations,

on the pure side, and

* cosmology, relativity, gravitation
* mechanics
* approximation theory and numerical analysis

on the applied side. He suggests that we are missing significant research groups in the following areas: complex function theory, potential theory and theory of several complex variables, abstract harmonic analysis with integral transforms and operational calculus, geometry and convex analysis, differential geometry.

5.3 Research Priorities

In formulating a research policy for mathematics, one has to be guided to some extent by those local factors which influence the nature and direction of mathematical research. For example, in SA the research community is small, and its resources are very limited when compared to those of the major first-world countries. Geographical isolation should also not be underestimated, although the advent of electronic mail helps to some extent.

In view of the basic nature of mathematics for all the other sciences, we should aim to have viable research groups operating in a significant number of areas of mathematics, both for its own sake and to provide a basis of expertise to call upon when carrying out research in more applied areas. The logical proposal would be to support those areas where we already have some strength, with the aim of maintaining a critical mass of researchers in each chosen area, but with a guiding view that, except for workers of exceptional ability who should be enabled to pursue whatever topic interests them, there is a case for guiding and preferentially supporting work more toward the applied end - differential equations and functional analysis, for example, or the applicability of finite mathematics in industrial problems, or of geometry and topology in theoretical physics - than the highly abstract. In particular one can suggest that there is a considerable need to build up the area of industrial mathematics.

Apart from this broad aim, there are three themes that can be proposed as a guide in directing future research in the area: a broad guiding principle, and two quite different aspects of mathematics in relation to computers that can claim special status as areas to be developed.

5.4 Interconnectedness as a Theme

Research mathematicians should reconsider their methodology, not necessarily their topics. The orthodox methodology of the research mathematician is that of specialisation/generalisation, where the emphasis is on the concept under investigation itself. This needs to be balanced with what may be called a lateral approach, in which the concept under investigation is viewed in its relationships with other concepts (Brink 1993). That is to say, there is not a problem with the investigation of abstract concepts *per se*. Rather, there is an overemphasis on the investigation of abstract objects in themselves and for their own sake, and an underemphasis on the investigation of abstract objects in their relationships to each other and to the real world.

With such a methodological rethink, the customary distinction between "pure" and "applied" research will be seen to be misleading. What we should strive for is the connectedness of research, so that "application" gets to be seen as relative to some other field of study – even if that field of study is also of an abstract nature. From this viewpoint, certain areas of 'pure' mathematics can attain a high priority - if they are seen as being related to many other areas, or serving as a fundamentally unifying theme for many areas.

5.5 Formal Aspects of Computer Science.

Amongst the topics that merit attention in this country, one deserving particular development is the interplay and interactions between mathematics and computer science, specifically the area of formal aspects of computer science.

Ever since Newton mathematics has developed in a symbiotic relationship with physics and the natural sciences. Now we have a new and similar relationship developing between mathematics and information sciences. Just as the mathematical toolkit of the natural scientist is built up from the differential and integral calculus, so the toolkit of the computer scientist is built up from discrete mathematics and the calculi of logic. In this new development fresh ideas and insights come from a wide spectrum of research activities; it is therefore a very promising area for the application of the methodological ideas above. In this country we have as good a chance as the rest of the world in making a significant contribution in this line of work – provided we can join forces.

Specific kinds of issues that might be addressed are knowledge representation, formal aspects of programming, and automated reasoning. Besides bringing a fresh perspective into mathematics such a development should have positive real-life spin-offs. To see this it is not necessary to envisage mathematicians suddenly turning into programmers, or computer scientists turning to proving theorems. It is only necessary to realise that there is good hard mathematics to be done here, that computer science can serve to direct our activities (in the same way as physics or the other natural sciences do), and that no science can grow without an active mathematical base.

5.6 Computational Mathematics

There is a good case to support the view that computational mathematics should be fostered as an area of mathematical research in this country. The general area of computational science is one which has assumed a position of major importance in research and development elsewhere (Zabusky 1987, Winkler *et al* 1987, NSF 1990). This fact has been recognised by many countries, which have allocated significant amounts of research expenditure in this direction. The importance of the computer as a problem-solving tool is well appreciated by the engineering community, to the extent that it is a central part of technological development as well as routine engineering practice. In the sciences, and in the mathematical sciences in particular (excluding the obvious case of computer science), while the computer now has a permanent role in the undergraduate curriculum and while there is country-wide a fair amount of emphasis placed on research of a computational nature, existing activity is not anywhere near the level which can, and arguably should be, sustained.

Computational science is by its very nature an integrated undertaking, and should be given attention as such. The aim here, however, is to highlight the place of mathematical research in computational science, and to show that mathematics which bears a close relation to emerging and continuing activities in computational science is worthy of attention, and is a particularly appropriate area of activity for this country's mathematicians to be involved in at this time in our history.

The subject of computational mathematics may be broadly defined as the collection of those mathematical activities which bear some relation to the computer as a problem-solving tool. This deliberately vague definition is meant to encompass a wide range of activities. For example,

(a) *Mathematical modeling*, in which complex processes are represented through systems of equations. These problems are almost invariably susceptible to solution only by computer. The algorithms to be employed, as well as the interpretation of results, in themselves represent challenging problems. A particular and striking example is that of computational fluid dynamics (including meteorology). The area of industrial mathematics offers many opportunities here.

(b) *Numerical analysis*, the speciality in which methods for solving systems of equations on the computer are developed and analysed. It is not enough to develop algorithms: the practitioner has to be satisfied they will be well-behaved in practice. Thus good understanding of the nature of errors peculiar to algorithms is essential. All of this forms part of numerical analysis. Applications in engineering and physics are numerous (finite element analysis of structures, studies of fluid flows, analysis of the nature of materials in solid state physics, and so on); they are also important for example in modern medical imaging (as in the CAT Scanner).

(c) Aspects of *functional analysis*, that part of abstract mathematics which provides much of the tools necessary in numerical analysis.

(d) *Differential equations*, which are the mathematical vehicle for representing continuous properties. This is a huge sub-discipline of mathematics, which has benefited enormously from the advent of the digital computer.

(e) It naturally carries over into areas often collected together under the name *artificial intelligence*, such as expert systems and neural networks. As an example, recently a neural network using Bayes' theorem to minimise errors won a competition for predicting accurately the energy consumption in a specified building (Geake 1993).

(f) It also carries over into the area of *algebraic computing*, in which computers are used for symbolic manipulations instead of numerical work, enabling them to carry out calculations in algebra and calculus as well as numerical analysis (which can be integrated into the same program).

(g) Finally, studies of *fractals* and *chaos* are necessarily based on use of modern computers. These are fascinating in their own right, and may be used to generate beautiful visual patterns; they also for example can be used in image compression.

The kind of computing carried out in the context being discussed is nowadays referred to as *scientific computing*; it is specifically aimed at solving complex systems of equations, together with the associated pre- and post-processing activities (preparation of data, graphical representation of output, and so on). Much of the effort is concerned with solving problems which are tractable only by computer, and then too only in an approximate way. It is worth emphasizing that scientific computing is not the same as computer science (or investigations of the formal aspects of computer science, just discussed); indeed, the expert in scientific computing is likely to be someone with a background in mathematics (pure or applied) rather than computer science.

5.6.1 Why Promote this Area?

a) It is a source of problems of great interest. The methods of computational mathematics play a central role in the solution of many problems aimed at arriving at a better understanding of the world we live in. For example, mathematical models of the behaviour of fluids have an impact in areas such as oceanography, astronomy, meteorology, hydrology, and medicine. The models even when they are not complex nevertheless exhibit complex behaviour (as in the famous Lorenz equations which arise in meteorology, and which have played an important role in the identification and study of chaotic behaviour). Furthermore it is generally the case that they are intractable without the aid of a computer.

Large scale simulations on the computer provide an alternative to expensive (and sometimes quite impossible) experiments, and furthermore provide insights which are quite remarkable and often counter-intuitive. This has led to the establishment of 'numerical laboratories' in which traditional theoretical and experimental work are complemented by computer simulations of processes.

A key test of any area of mathematics to being worthy of attention is the extent to which it interacts with and opens up new areas of enquiry. Computational mathematics has had an extremely fertile interaction with a wide range of the standard specialities of mathematics. Perhaps its most visible influence has been on the speciality of numerical analysis; a large part of this subject is today devoted to the creation and study of efficient schemes (algorithms) for solving complex problems by computer. In order to carry out serious research in this area it is important that numerical analysts in turn be acquainted with subjects such as functional analysis. This speciality, for many years regarded as strictly a part of pure mathematics, is today experiencing a resurgence of popularity as an eminently applicable part of mathematics. Indeed many important areas of investigation in functional analysis have been suggested by problems which have their origins in computational mathematics.

More generally, as mathematics moves into an era in which the importance and relevance of nonlinear phenomena are realised, so too does computational mathematics come into its own as a vital part of such investigative efforts. The subject of dynamical systems, and in particular chaotic dynamics, is a case in point, as is the subject of fluid dynamics, in which the quest for a definitive mathematical description of turbulence has led to remarkable mathematical advances.

From the above it should be clear that, within the broad ambit of computational mathematics, it is possible to accommodate mathematicians of widely varying interests and backgrounds.

b) The subject is integrated by nature. Research in computational mathematics lends itself in a very natural way to integrated research, in which mathematical specialists of different kinds interact with physicists, engineers, and other scientists. Within mathematics itself the area provides ample opportunities for pure and applied mathematicians to interact, thereby helping to bridge the unfortunate gulf that has arisen between these two aspects of mathematics.

c) Research in this area provides important practical skills. There is at the moment considerable debate in the USA about the role of a PhD degree in mathematics. This debate has been prompted by the difficulty which many PhD graduates in mathematics have in finding employment outside the universities. Postgraduate research in this area can provide many of the skill that would enable graduates to enter the job market and play a role in the general economic development of the country. For while the place of computers in engineering and technology are generally understood, what is equally important is that this country trains graduate scientists, necessarily at the masters and Doctoral level, who are able to make use of the mathematics they have learnt. It is precisely in the area of computational mathematics that so much of that part of mathematics considered 'pure' (meaning devoid of applications) in fact finds application, both within and outside mathematics.

5.6.2 How should Computational Mathematics be Promoted?

In SA it has been difficult to arrive at a critical mass of teachers and researchers in computational mathematics, given the demand for them outside universities and outside the country.

a) *Publicity.* Researchers in allied areas (mathematical physics, functional analysts, mathematical modeling) should be made aware of the possibilities offered by the subject, as should students wishing to undertake mathematical research in the mathematical sciences. It may be worth organising a workshop or conference whose specific aim is to inform researchers and students of the possibilities in the area. Furthermore inter-subject research should be encouraged through facilitating teams of researchers drawn from different disciplines.

b) The *experience of other countries* should be studied, as for example in France where a few outstanding mathematicians recognised the importance of research in numerical analysis and scientific computing, as branches of mathematics.

c) The *undergraduate curriculum.* Some of the enthusiasm generated by workers in the area should be transmitted to undergraduates by giving them an idea of the relationship of work in their current subject to some of the more interesting advances being made. For example the subject of chaotic dynamics can be fruitfully discussed in courses on modeling, differential equations, discrete mathematics, functional analysis, numerical analysis, fluid and solid mechanics, to name just a few areas.

d) *Existing skills* should be used as a base. There is limited activity at some centres in SA (Wits, UOFS, UCT). Clearly such centres should be used as the germs of an expanded effort.

e) *Links with industry.* There should be considerable interest in industry. Links with industry should be sought and nurtured; even when financial support from industry is not forthcoming to the extent desired, industrial problems remain a fertile source of important ideas in this area.

f) Some research projects will require considerable *computing power.* However it is not necessary to indulge in an orgy of acquiring computing power for its own sake. There is much that can be done with modest computing facilities, and this is where one should start. Questions related for example to vectorisation and parallelisation are occupying a great deal of effort in developed countries; it will be a little while before we are able to address these issues here. What we need first are groups of people who have the enthusiasm to do research in the area; with highly motivated research groups, more physical facilities will follow.

5.7 Equipment Required

The main equipment required for mathematical research, apart from the ubiquitous books and journals, is computers of adequate power. In view of modern progress in computers, this should not be excessively expensive: it is likely that most of the needs can be met by modern desk-top work-stations.

However there may possibly be a case for establishment of a super-computer centre as a national facility for use and research in computational mathematics and information technology, but available as a common facility to all other interested sciences and applications. For example it might be anticipated that there would be a need for use of super-computers in theoretical studies in material science. The case for such a centre would need careful consideration.

Chapter 6

Statistics

Statistics is the basis of the analysis of data in all the sciences, as well as in much of management, where far-reaching and costly decisions have to be made in the face of imperfect knowledge.

It is based on mathematics, and finds application in the social sciences, meteorology, biology, physics, astronomy, engineering, indeed in any subject where society, nature, economics or manufacturing processes are studied in a quantitative way.

The central theme of statistics is the application of probability theory to the collection and analysis of data from phenomena which are subject to variability. The bases of data collection rests on sampling and experimental design. Statistical inference allows characteristics and relationships present in the entire population to be inferred or predicted by examination of data from only a small portion of the population. A closely related discipline is that of *Operations Research*, which offers a a numerate approach to decision making in industry, government, and commerce by means of data analysis, simulation, and optimisation theory. Use of the methods of statistics and operations research have amply proved their value and can lead to very large savings of time, money, and other resources, and also to a deeper understanding of the world around us.

While the basics of statistics are well developed, there is a need to reshape statistical tools, and possibly invent new ones, for each application which is not completely standard. The ultimate goal of statistical work is the valid and reliable interpretation of the data. An understanding of the difficulties of sampling and measurement is needed in each problem before a satisfactory solution can be found. Statistical theory gives the yardstick by which the quality of the data and its analysis may be assessed, and allows us to decide how far the conclusions drawn can be trusted.

6.1 Statistics in the South African Context.

The discipline of statistics will play a vital role in the development and reconstruction of SA. There is a great need in our society for basic applied research addressed to local problems, and the statistical content of that research is high. Participation of statisticians as equal and active collaborators in such research, rather than simply as advisors, will ensure

1: efficient study designs,

2: appropriate analysis of data,

3: valid and reliable conclusions.

Such participation and collaboration should be encouraged to take place not only among colleagues within the universities but also with scientists, economists, health workers and sociologists working in Government institutions and in industry. The expertise statisticians can offer can play a vital role in planning and restructuring. In fact no proper decisions can be taken without reliable information, and such information can often only be obtained by statistical methods.

Some of the collaborations may only involve routine statistical methods but others are sure to highlight the need for development of new methods and theory. Thus it is important to foster purely theoretical statistical research alongside the practical applications.

Throughout the history of the subject, the best and most enduring statistical methods have been motivated by practical problems. With support, in SA we have the ability to produce new statistical methodology that will not only meet the needs of local problems but also have world-wide application. It is of course important to maintain close links which we have at present with the international statistical community to avoid duplication of effort and to ensure that our work satisfies the exacting demands of international scholarship.

As has been emphasized above, the applications are many. We may perhaps expect the main themes of statistical research in the future to continue as in the past, best characterised by the applications involved rather than the particular techniques used.

6.2 Bio-statistics.

Biostatistical research falls into two broad categories:

1. The bio-medical field, which deals with human populations and their well-being, and

2. The environmental field, which deals with plant and animal populations and the factors which affect them

6.2.1 Biomedical Research

Apart from the time-honoured application of statistics in clinical medical research, new areas requiring urgent statistical collaboration are rapidly opening up in SA. Much of the international research in medical biostatistics has been undertaken with a view to application in a first-world setting. The problems that arise in health research in the developing world such as the mobility of population groups; the difficulty of follow up; incompleteness of records; inaccuracy of information on population sizes, pose particular challenges that need to be tackled in a coherent manner.

Epidemiology is currently undergoing a phase of rapid development due to the influence of biostatistics which has reshaped both it concepts and its techniques in a fundamental way. Many of these new developments are of particular relevance to SA health research. SA with its combination of highly skilled biometricians and epidemiologists and its less developed circumstances presents a challenging and rich environment for substantial research into both theoretical and applied problems. Innovative methods are continually required to investigate even simple phenomena owing to the absence of reliable secondary data sources.

Some specific areas where statistical research is needed are discussed next.

1. Public health. Community health, environmental health and occupational health are areas of research that are new in SA, but which are going to be of increasing importance. Although much of this research has a large statistical component, only elementary statistical methods have been used so far. Many recent statistical advances which could yield much fuller insights into the data have not been used. There is a need to implement these methods in a SA setting and develop a more sophisticated epidemiology.

Among the public health issues which present statistical challenges are the following.

(a) *The AIDS epidemic.* This has not yet peaked in SA, and its course must be monitored, the costs of treatment of AIDS cases must be estimated and a rational approach to meeting these costs devised. The distribution of Aids in Africa is different from Western experience, so while one can draw on research from the developed world to some extent, research is needed into the nature, path and social consequences of the disease locally.

(b) *Malaria.* The new and virulent form of malaria is a challenge to the medical and health authorities. Statistical mapping of its spread and evaluation of control measures adopted is needed.

(c) *Measles and other infectious diseases.* Measles, gastric enteritis and other infectious diseases take a heavy toll on our young children, particularly those who live in crowded urban environments. These are preventable diseases and, again, evaluation of the effectiveness of control measures is needed. Furthermore, modeling of the spatial dynamics of the incidence of infection could lead to biologically more realistic models of the spread of epidemics.

(d) *Occupational health.* Concern for the well-being of workers in industry has not played a large role in SA in the past. Protection of workers against exposure to harmful conditions in their places of work and compensation for health problems arising from exposure will receive higher priority in the future. Statistical modeling of disease-exposure relationships will form an essential part of this process.

2. Vital statistics. There are particular challenges facing SA demographers. The SA population is a mobile one and thus is hard to count. Effective planning cannot take place without good information on population numbers. Furthermore, for the information to be useful, it should be collected and stored in a way that makes it accessible to researchers in any field. In the health field there is a need for more detailed information on the size and age structure of local populations so that public health programmes, such as, for example, the immunisation of children can be more effectively implemented and their progress monitored. Moreover since the population is so mobile, five yearly census data is not useful. Methods for more rapid assessment of population sizes should be developed. More detailed and explicit recording of causes of death would make these statistics a more useful monitor of the health of the nation.

6.2.2 Environmental Bio-statistics

In this section we consider some aspects of research into our natural environment and into its sustainable development and shall outline areas where further statistical research is needed.

1. *Sizes of plant and animal populations.* The present method of assessing the size of plant and animal populations are expensive and often take highly trained observers a long time. There is a need to devise sampling methods that would allow more rapid assessment, without losing too much accuracy. Furthermore these methods must allow reliable comparisons from year to year and from place to place, so that population changes can be detected. There is also a need to develop methods that can reliably be used by relatively untrained observers.

2. *The Fynbos biome.* The Fynbos of the western and southern Cape is famous throughout the world for its astounding diversity. For this alone it is a precious national asset, but moreover, through the flower industry, it provides employment for a large number of people in areas that are otherwise poor agriculturally. Statistical methods have been effectively used to gain insight into the ecology of the Fynbos, but there is room for much further research into appropriate methods here.

In particular application of recently developed methods for the joint modeling of both the mean and the variability could give quantitative understanding of both the biological factors that affect the fynbos, and the environmental factors that interact with them.

3. *The Benguela upwelling.* An understanding of the biology of our coastal waters is important both for scientific and economic reasons. Sustainable exploitation of the coastal waters and fishing industry is of great economic importance to SA. The further development of good statistical procedures to aid decisions on fishing quotas is an area which should be actively pursued. Assessing the size of marine populations is even more difficult than assessing the size of terrestrial populations and yet it is essential to attempt this to avoid ruining a precious asset. Research is needed into sampling methods which give improved estimation of the size and variability of fish populations.

4. *The Oceans.* The physical properties of the ocean around our coast are of world-wide importance. The modeling of sea-surface temperatures and their impact upon our climate present challenging statistical problems.

5. *Avian demography.* SA has led the African continent in the study of bird populations and their migrations. Large data sets already exist. The information they contain is of international importance. Attempts must be made to advance and improve their statistical analysis and devise modeling techniques so that the best possible use is made of this valuable information. Birds are sensitive to climatic change. The present data bank could be a reference point from which this change could be assessed. To do this, research into appropriate statistical monitoring techniques is needed.

6. *Hazardous waste.* Hazardous waste is both generated by our own industries and imported from industries overseas. Its disposal must be managed so that the risks of catastrophic damage to the environment and human or animal life are minimised. There is substantial scope for statistical research in this area.

7. *Agriculture.* Statistical methods have played a fundamental role in agricultural research in SA. These methods will continue to be important and new methods will need to be developed as agriculture faces both changes in its economic structure and possibly climatic change.

8. *The Environment and International Agreements.* SA has responsibilities towards international agreements on protection of the environment, such as the Ramsar Convention on wetlands, the Bonn convention on migratory species and the Rio declaration on bio-diversity. Adherence to these will involve some statistical monitoring, and research needs to be done on the most appropriate methods.

6.3 Water Affairs

The ultimate restriction on growth and development in SA will be its water supply. Much of the information on water supply is statistical in nature and good statistical theory can ensure that this information is used to the best advantage. Some current research which is yielding useful results and should be encouraged is discussed below.

6.3.1 Droughts and Floods

Statistical modeling of droughts and floods and the modeling of the spatial and temporal distribution of rainfall is an active area of research, which , because of its importance, should continue.

6.3.2 Provision of Water

The simultaneous demands by communities, agriculture, and industry for provision of water and the demand of environmentalists that its provision should not harm the environment, presents an extremely difficult problem to any decision maker, who has to reconcile these conflicting demands. Application of the theory of multiple criterion decision making can help provide a rational solution to this problem. Under a facilitator, through consultation and discussion each interested party can express reasons for their requirements and become aware of the impact their demands would have on other parties. The facilitator can then present them with a number of possible decisions. Each of the decisions satisfies the requirements laid down by each party to some degree. The theory of multiple criteria decision making gives a means of ranking these decisions, to find the best ones. Computer software to implement this methodology has been developed locally and is at present being tested.

In the massive programmes of upliftment that will have to be undertaken in the development of a new society, we shall be faced with many situations such as the one outlined above. There is a vast potential for the application of the methods of multi-criterion decision making as an aid to making rational decisions about the allocation of scarce resources. Further development of this method should be encouraged.

6.4 Industrial Development

Much of the success of Japanese industry can be directly attributed to the incorporation of statistical methods as an integral part of the manufacturing process. Each stage of the development of a product is subject to rigorous statistical scrutiny, until the product can be manufactured without defect. The so-called Taguchi methods have been so successful that they have attracted world-wide attention. No country wishing to compete in world markets can afford to ignore them.

Successful as the Taguchi methods have been, they are still in need of much theoretical and practical development. Involvement of statisticians in research directed at industrial development and at some of the problems which are specifically encountered by our industry could benefit the country enormously.

6.5 Economic Development.

Unlike the rest of Africa, SA has reliable and sophisticated economic statistics. However our economy has large informal sector whose contribution is not reflected in the standard measures of economic activity. Ways of measuring this contribution to the economy is a statistical problem facing econometricians.

The economic restructuring of the economy of our society that will take place over the next few years will raise many contentious issues such as,
1. the Nationalisation debate;
2. the modus operandi and financing of redistribution, whether by income tax, a wealth tax, or World Bank aid;
3. the role of public works in effecting redistribution;
4. the desirability of minimum wage legislation in the face of severe unemployment.

All these debates are worthy of empirical evaluation, but present statistical problems, particularly in the measurement of the impact of different policies. In addition, policy changes tend to have long term effects which are difficult to disentangle from other short term effects. Moreover the SA economy is inherently volatile which makes the measurements and analysis much more difficult.

6.6 The Needs

There are opportunities for demanding and exciting statistical research motivated by the challenging problems facing our country. The results of this research could have an enormous impact on the solution of these problems. There is a strong case for inclusion of the cost of statistical design and analysis as a specific item in the research budget of almost all project proposals, so that a statistician can be part of the project team, or at least act as a consultant.

Theoretical statistical research motivated by practical problems needs to be supported to ensure that new methods are based on a firm footing. To avoid duplication of research, the strong links that SA has at present with the international statistical community should be maintained. Post graduate studies in statistics should be supported to ensure that SA will be able to produce enough highly qualified graduates to meet the undoubted demand that exists in the country for statistical expertise.

6.7 Equipment Required

As in the case of Mathematics, the main equipment required (apart from books and journals) is computers of adequate power, which should not be excessively expensive, and application software.

Chapter 7

Information Technology

The broad area of information technology includes both Computer Science, and Information Technology proper.

Computer Science is the study of the architectures of digital electronic computers, and of the theory underlying their use. This is the basis of the information revolution that is presently transforming all aspects of science, engineering, and commerce.

The two main areas of research are *hardware*: its logic, structure, and integration, and *software*: compilers and assemblers, operating systems, communications and networks, databases, programming languages. Computer Science Research into applications involves study of *general principles* applying to all cases: algorithms, software tools, software engineering, and complexity study (the study of resources - time and storage - required by an algorithm).

Information technology: (IT) is taken here to be the broader study of all areas concerned with the processing, transmitting, and meaningful display of information, including computer science, study of the human-computer interaction (including design of user interfaces), information theory (particularly dealing with the issue of noise), and the electronics of communication. It includes study of the bases of *particular applications areas*: computer images and vision, Computer Aided Design (CAD), Computer Integrated Manufacturing (CIM), Robotics, Management Information Systems (MIS), Artificial Intelligence including neural networks. As these studies involve for example psychological and economic issues, this is an interdisciplinary area.

There are numerous specialised applications in science, engineering, commerce, and industry that are studied as branches of other subjects (applied mathematics, statistics, physics, business science, and so on); this is where detailed development of applications takes place.

Information technology defined in this broad way is one of most important technological influences on society today. The social importance of the field lies in the potential for applications and the profound social impact of these applications. Computers can provide significant benefits to the people of this country in many social contexts. Applications range over earth science and resource mapping, education, community information banks and electronic libraries, health care, not to mention the obvious applications to small business support, manufacturing support and network services.

7.1 Present State of Computer Science

It is fortuitous that Computer Science is itself experiencing an identity crisis world-wide. Funding bodies and Computer Scientists are changing from investigating the machines to investigating the way they may be used in the community. The machines are underused because of a breakdown in communication with their potential users: out of the range of possible ways they could be used, we are seeing only a few.

World-wide, the profession is in a state of transition. The U.S. National Research Council (1992) has recently issued a report that recommends that Computer Scientists broaden their conceptions of the discipline to include computing applications and domains to help understand them. Usable research is necessarily multi-disciplinary and broad research. The current name of the subject still reflects the old research emphasis. An alternative that reflects the importance of information is possibly *Informatics*, but in fact the switch is from emphasis on computer science to information technology.

Thus research is changing its emphasis from concentrating on machines to considering the relation between Information Technology and People. Its traditional areas of research are less in need of advancement. Developments are such that the inherent power locked up in a computer system far outstrips people's ability to use it. Research to make machines more useful involves particularly databases, distributed systems and networks, and most importantly, especially for SA, human-computer interaction.

7.1.1 The South African Situation

Computer Science is currently not very highly regarded as an appropriate field for research and development in this country. The profession of computing is divided. There is no Information Technology Society or individual Computer Scientist who can make SA policy makers sit up and take notice.

7.1.2 Low-tech is Best in South Africa?

The crudest condemnation of Computer Science is to regard it as the exemplar of inappropriate high technology. Inappropriate because SA is underdeveloped and so 'obviously' does not need Computer Science. This is dangerously wrong: it is not the case that high technology is only suited to advanced countries.

To lead in a very advanced technology, as in the USA or Japan, often carries the burden of a large investment in *current* technology. However redressing relative underdevelopment, as in this country, can allow one to follow a few stages behind: to leapfrog several stages of technological development and avoid expensive blind alleys. Very advanced technology can be easy to use: the details can be made to "disappear", removing the distraction of the technology and enabling concentration on attaining real objectives. Advanced information technology can then be used to provide very simple and effective tools (word processing, data bases, CD ROM encyclopedias, ...) for tackling local problems. However current computer applications still intrude their computerishness on us when we use them (e.g. word processors require saving the document before switching off; installing modern computer programmes while keeping the system compatible is a tedious and time-consuming exercise).

This is where research is required: to get rid of such intrusions, providing the facilities so that computers solve the problems of, and enrich and entertain, people who are not computer junkies. Here is where local research and development can be important.

A variation of the criticism is to recognize that certain more advanced tools are needed. However, it is argued, such tools need not be researched and developed here; all our needs can be satisfied by imports. There is *indeed* a global market in this technology but there are niches for local products. There are local problems which the rest of the world does not intend to address. Without local expertise of international standing one also becomes dependent on the vested interests of others. We cannot rely on the benevolence of 'developed countries' to provide us with solutions: - if we don't know what we are doing, we will be ripped off in a big way (e.g. by being sold obsolescent machines). Finally, the so-called third world is very well placed to gain significant commercial advantage in sectors of computing such as software development.

The industrial world is changing and computers and communication technologies are producing revolutionary changes whose effect will of necessity be global. No country can avoid this without incurring a new and crippling form of underdevelopment. The global economics of Information Technology requires our country to have researchers and products of international stature, and to have access to international networks in order to keep up with the latest trends.

7.1.3 Structure and Funding of Computer Research.

Most research in Computer Science in SA is divided between Computer Scientists and Electrical Engineers. Funding bodies will often support research and development in the engineering and application fields provided it "is not just software". What is needed is research into how to the produce better software and computer systems, and how to measure desirable and undesirable qualities of software and systems.

Applied Computer Science is also split between Computer Science proper, and Information Systems. *Information Systems* (as the term is commonly understood in South Africa) is about money and management, and researchers are in practice commercial consultants. For successful application development the computing community must gain reliable knowledge of design and uses of computerized systems. This has hitherto been left to Information Systems. However the narrow focus of Information Systems (mainly on imported products) has prevented the exploration of new possibilities and the recognition of the role of local researchers. It is questionable whether Information Systems has served the interests of business well by relying so much on imports, without developing local expertise sufficiently in distinguishing good from bad. There is a strong reliance on consultants: but then how do you tell a good consultant from a charlatan?

Scientific research sometimes defends its purity by steering away from applications. However we do need research on measuring performance of purported better approaches to applications. On the other side, commerce and industry do not accept the relevance of local researchers, and apart from some significant exceptions, innovation is seen as something to be imported from the first world; not something to be produced here for local requirements or exported.

These are *not* the preconditions for practical, useful research and development in Computer Science for this country. Local development of usable software is practicable and important; computer science can support that development, *inter alia* by helping design policy that encourages local software development. A critical policy issue that has to be resolved is how to support and evaluate Practical Information Technology Research.

7.1.4 The Focus on Usability

Mathematics is traditionally regarded as the foundation of Computer Science. However mathematics and formal methods by themselves give little insight into why and under which social conditions some systems perform better than others. This is not to say that mathematical methods are not useful. However the technology has reached a state of maturity where the nature of the problem deserves an extended emphasis encompassing "design for use", and evaluating alternatives for usability.

The South African Foundation for Research Development (FRD), still regards Computer Science as a part of mathematics. This results in a negative attitude to researching building useful systems. Making computers useful to people is not regarded as an appropriate research venture in that the FRD does not consider Human-Computer Interaction as a legitimate research field. Yet this is one of the key areas of activity for computer scientists who wish to make computers useful.

Realistic graphical displays provide intuitive insights into data that are not captured by formalism. Visual interaction with a computer system provides understanding not available from even the best symbolic language. Networking and personal computers push computer applications into milieux where they were previously unknown and where traditional methods fail to predict effectiveness.

Once the research emphasis shifts to embrace people and once the importance of Human-Computer Interaction is recognized, one can re-examine more traditional fields of research in Computer Science. Their importance remains; artificial intelligence, computer architectures, databases, formal methods, networks and distributed systems, operating systems, programming languages, software engineering, symbolic and numerical mathematics, are all clearly important (so the new emphasis does not deny what was said in Section 5.5; rather it is complementary to what is said here). However one must recognise the limitations; for example Artificial Intelligence, the darling of the 'fifth generation', was over indulged. It turns out that difficult problems cannot be solved fully automatically; they require people to help solve them. Research is now concentrating on tools to help people carry out their activities. Artificial intelligence correctly regarded is a branch of human-computer interaction.

There has been a world-wide revolution in terms of "people's computing". Over 100-million personal computers have been sold world-wide and with the growing acceptance of windowing environments and plug-and-play peripherals etc., this is putting huge amounts of computing power in the hands of inexpert users; they are increasingly using databases, distributed systems, and networks. In this context, research on the Human-Computer Interaction, supported by reasoning systems and software engineering, is of great significance.

7.1.5 The Desired Future

Computer Science research can provide local solutions to problems in several important fields, provided the current fractious isolationism is avoided. Information technology can be a major export product and employer. It is an obvious industry for regions with few natural resources since its infrastructure can be provided easily and the main requirement is educated workers.

The main driving force for change in Computer Science is concern for the development of the country and its people. There is concern for the future of the Information Technology industry in South Africa and for the consequences for the country if we lag behind and become mere consumers of information and other higher technology products. We require people and solutions of international calibre, together with a recognition of the true nature of information technology.

7.2 Context of Information Technology

It is, first, a technology, and second, a technology in which there is intense development taking place on an international scale.

By characterising it as a technology we emphasize that it is much more than an academic discipline: it includes a series of tools and devices which has a very wide impact on society. In considering IT within science and technology policy, therefore, it is essential to view IT primarily in terms of its technological impact.

In noting that IT is currently a focus of major international development, driven by the explosive development of integrated circuit and storage technology, we emphasize that changes and developments in the tools, devices, standards and procedures which constitute IT will be affected only marginally by developments in South Africa. On the whole, we will adopt new developments in IT as they become available from overseas. We will thus be users and recipients rather than creators and drivers. It can also be noted that South Africa has a record of rapid assimilation of new information technologies, and of innovation and energy in applying IT (with some exceptions, for example adoption of RISC-based Unix servers to replace mainframes).

A clear Information Technology policy will also consider freedom of information, data protection, rights of the consumer as well as the vendor, and privacy issues and protection from intrusion (hacking). Of particular importance are copyright law and the recognition of international regulations on software protection on the one hand, and consumer protection legislation on the other. The current GATT round is concerned with intellectual property rights and the international recognition of patents on software and algorithms will have a very negative impact on the ability of new countries to enter the international software production market. Research is needed on all such aspects of IT policy.

7.3 Impact of IT in the New South Africa.

IT will contribute both to competitiveness and to improved living conditions. The hightech, first world area is the clearest. International competitiveness in manufacturing and provision of services is heavily dependent on IT, ranging through such issues as access to global communication networks, computer aided design and computer controlled manufacturing, electronic data interchange, adherence to common standards, complex engineering software, and a number of others.

Less obvious is the role IT can play in raising the quality of life of the disadvantaged in South Africa. It can be anticipated that moves towards a cashless society will continue, with particular use being made of smart cards; immediate issues are pre-payment cards for such services as electricity and water. It can be anticipated that IT will become increasingly used in educational technology, bringing almost all primary school children into contact with computers. Books can now be more cheaply produced on CDROM that in conventional form - library resource centres at schools and community centres might be able to use this technology rather than books. Automatic teller machines (ATMs) are already widespread, and it can be anticipated that their use will be extended both in terms of users and services offered.

7.4 Educational Policy in Respect of IT

We believe it is important that children be introduced to the computer early in their school careers, preferably in primary school. What is required, however, is that IT be taught as a life skill and not as an additional academic subject. Schoolchildren should become familiar with the concepts of word-processing, spreadsheets, networks, and electronic mail; the emphasis should be on applications (such as the use of systems in retailing, banking, schools, and government) rather than on topics such as programming in BASIC, although that side should not be entirely neglected.

At the tertiary level, including both technikons and universities, computer science and information courses are in great demand, and the demand seems to be growing. Information technology also plays a major role in almost all engineering courses and a number of science courses, covering range of hardware and software applications.

Computer skills at all levels are an asset in the job market. It seems unlikely that this will change in the future. The conclusion is that the teaching of information systems, computer science and computer engineering should be encouraged and strengthened; this will benefit both individuals and the nation in that a computer-literate work force will contribute to the achievement of external and internal goals.

A major point here is the need for education in how to choose the best computer systems for particular purposes, and making sure that software bought off-the-shelf is used to best advantage. There is a big pay-off here. This is really a matter of educating the public in usability; which is based on analysis of how one tells what are the best systems and the best ways of using software.

7.5 Research Policy in Respect of IT

In general, as pointed out above, developments in IT are proceeding at a rapid rate in all the developed countries, and very considerable financial investments are involved. It is unlikely thus that South Africa will contribute materially to these developments. Nevertheless in order to ensure that teaching at tertiary level is maintained at the leading edge of international developments and in order to train high level manpower, research must be carried out in information systems, in computer science, and in applications in engineering and science including in particular the human-computer interface in the context of local applications.

This research should be directed primarily at the maintenance of the pool of knowledge and skills across the spectrum of subjects, and in how to promote the rapid adoption and application of information technology to address business and societal problems. There is in particular a need for an educated community in making intelligent decisions without relying on outside experts whose motivation cannot always be controlled to fit the needs of society. This requires a properly populated hierarchy from technicians through researchers, as all these areas relate to each other in a synergy. While research with obvious and direct application is easy to support, there is a place for theory too as applied research draws on theory.

However there are some potential niches where local development could have a significant impact, even leading to export of locally produced products. These include such topics as interfaces for touch and voice operated computers, the developments of standards for Africa (for example the design of icons and protocols for user interfaces), language translation (in respect of African languages), and specific application development in the engineering, scientific, management, and educational areas where there are specific niche needs to be met. They could conceivably lead to production of specialised chips (ROMS) or CD disks. In each case development involves building pilot systems. Prototypes and systems need to be tested and evaluated against norms.

The challenge to computer science is to provide the required expertise and methods to make this development effective and efficient. This requires research into design principles and methodology, but also involvement in the applications which are the goal of those principles and methodology - for without this involvement, the research will be likely to be academic and sterile. Probably these applications would be best tackled by teams involving both computer science specialists and researchers involved in depth in the application area, leading to a two-way learning process informing both areas of expertise. An interesting development are exploratory talks regarding establishing a Western Cape Regional Visualisation Centre, to study ways one can help users faced with complex data can gain insight into that data through exploratory visualisation, which can also enable one to communicate these insights effectively to others.

As emphasized above, we need research on how one tells what are the best systems and the best ways of using software. You cannot be sure they are better unless you can measure something. Such tools research is actually very difficult to do well, because the real measure is not the tools but what you can produce with them. Thus in fact usability should be regarded as a key research area.

7.6 Development Policy

Matters of industrial and commercial development in the IT area fall beyond the scope of this document. However insofar as they relate to research and the production of high level manpower, it would appear that there is potential for growth of the local software engineering industry, contracting services in the international market. In this respect, university and technikon departments should maintain close links with the commercial software houses and the other organisations intimately involved in developments in IT. For their part researchers should recognize that Technikons are potentially excellent partners in the development of applicable Computer Science.

A major need in the development area is that of information systems development at universities and technikons. Further, the use of information technology by government should be improved, particularly in areas such as census, voting, identity documents, tax, and social services. This is not, as is sometimes alleged, merely an issue of programming ability; rather it is development of the 'human-computer' interface in the wider sense of ensuring that the use of the computer is in fact efficient and beneficial in its applications in society.

Thus there is interesting research to be done here on the social impact of computerisation and ways in which computer system design and use can be beneficial to society (which also implies understanding the ways it can have a negative impact). Understanding these issues is the broader challenge to information technology.

In terms of making computer usable, as well as the HCI research emphasized above a need is to make people aware of the best ways of choosing computer tools, for example only purchasing on the basis of adequate requirements analysis. This kind of education - and determining how best to convey such issues to the public at large - is again part of the wider scope of information technology.

7.7 Equipment

In this rapidly developing area, it is essential that workers are kept in touch with the latest technologies. There must therefore be provision for purchase of the latest hardware and software on an ongoing basis, if the research undertaken is to be internationally competitive.

B: Natural Sciences

Natural Sciences is used here as a label for the basic experimental and observational sciences, apart from the life sciences and the earth sciences (considered separately below). One could perhaps follow another tradition and label the subjects here as *Physical Sciences*, that is, science applied to the inorganic world, as distinct from the study of the organic world. We have chosen not to follow that path because (a) we have separated out the earth sciences from the subjects discussed here, and (b) physics and chemistry do indeed have many applications in studying biology.

Thus this section includes 4: Astronomy and Astrophysics, 5: Physics, 6: Chemistry, 7: Materials Science. We have included the latter as a separate topic because it is an integrated subject including components from both Physics and Chemistry.

Chapter 8

Astronomy and Astrophysics

Astronomy: is the oldest exact science, in which the heavenly bodies (the Moon, the Sun, planets, the stars, nebulae, galaxies, etc.) are studied by means of observations made by telescopes of various kinds. It gives us our understanding of the large-scale environment around us, enabling us to grasp the nature of the solar system, the earth as a planet, and the sun as a typical star situated in a typical galaxy. It is the basis of our attempts to understand the origins of the solar system, the galaxy, and indeed the universe, and so provides the physical context for theories of the nature of the universe.

Observational Astronomy may be characterised either by the type of object observed: solar system, stellar, galactic, or extragalactic astronomy; or by the wavelength of observation (and hence the type of equipment and expertise needed to carry out the observations): namely optical, Ultra-violet (UV), Infra-Red (IR), microwave, radio, x-ray, or gamma-ray astronomy. There is also the possibility of difficult and costly types of observation through neutrino and gravitational-wave telescopes. *Theoretical astronomy* can be classed as celestial mechanics, astrophysics (use of the laws of physics to the study of stars and the gases between them), high-energy astrophysics, or cosmology (study of the physical universe as a whole).

8.1 Current Position

Astronomy is a branch of the physical sciences in which South Africa has been able to excel, largely through our geographical position, our climate, and the small but strong school of astronomy that has existed here for many years. As a result, this country is one of the leading contributors to astronomical research in the world, despite the relatively small numbers of astronomers resident here and the modest nature of the equipment available to them.

To discuss work done in this country, the field may conveniently be considered under four headings:

1. Astronomy at optical and infrared wavelengths
2. Astronomy at radio wavelengths
3. Astronomy at gamma ray wavelengths
4. Theory (including theoretical cosmology)

A good summary of astronomy in SA is contained in Whitelock (1993).

8.1.1 Astronomy at Optical & Infrared Wavelengths

The facilities for optical/infrared research in South Africa are concentrated at the Sutherland site of the National Observatory (the South African Astronomical Observatory = SAAO) with the main library, workshop and computer facilities at the SAAO headquarters in Cape Town. The SAAO is administered by the FRD although it is understood that funding is decided at the Treasury level. Annual cost in 1992/3 was R6.2m.

The staff of the SAAO have overall responsibility for the motivation (in conjunction with users), design, manufacture and maintenance of equipment and in making it available to scientifically qualified South African and overseas astronomers (and their properly supervised students). They carry out major astronomical research programmes. The non-SAAO South African users are generally from the universities. The overseas astronomers using SAAO are either from universities or from national observatories such as the Royal Greenwich Observatory. Currently observing time is granted to about 30 overseas groups annually, and the demand exceeds the time that can be allocated. Overseas users have come *inter alia* from the UK, USA, South America, Japan, Hungary, France, Germany.

South African astronomers, besides carrying out individual research and collaborating actively amongst themselves, play an important role in international collaborative research projects. These generally take one of four forms:

(a) Collaboration involving the use of similar telescopes and/or other equipment world-wide, to make detailed observations of a particular object over limited periods of time. An example is the 24 hour a day coverage of rapidly varying objects obtained with the "Whole Earth Telescope" (WET) project, of which SAAO is a part.

(b) Multi-wavelength studies involving both ground based and space based telescopes, e.g. X-ray, far-ultraviolet and far infra-red observations from space together with optical and infrared observations from the ground. Amongst this type of work are studies of active galaxies and celestial X-ray sources. This work often requires simultaneous or quasi-simultaneous observations from the ground and from space.

(c) Combining the unique facilities or observing conditions of different institutions for major programmes. For instance the advantage taken by the Oxford (UK) group of the superior photometric conditions at SAAO to calibrate accurately their major programme on the large scale distribution of galaxies in the universe (other parts of the programme being carried out in Australia). Another example is the current large sky survey, the Edinburgh-Cape blue star survey, which involves specialised facilities in Scotland, South Africa, and Australia.

(d) Collaboration between individuals or groups in South Africa with astronomers elsewhere, the different groups being expert in different aspects of the work on hand.

In addition, the University of Birmingham maintains a fully automated telescope at SAAO as part of their global network to monitor solar oscillations for the study of the internal structure of the sun.

8.1.2 Astronomy at Radio Wavelengths

The main facilities for radio astronomy are at the Hartebeesthoek radio Astronomical Observatory (HartRAO) in the Transvaal. The organisation of this facility (under the FRD) and its general purpose parallels that already mentioned in the case of SAAO. The annual cost in 1992/1993 was R2.9m.

Besides in-house research and the provision of facilities for South African university groups (Rhodes University has a strong group that uses HartRAO and produces higher degrees), one of HartRAO's major contributions has been to the world-wide VLBI (very long baseline interferometry) work, in collaboration with Australia, Germany, USA, and Russia. This is used to obtain high resolution radio images of such objects as quasars. The method is also used for precise measurements in geodesy (e.g. the movement of tectonic plates). The importance of HartRAO to these programmes is its unique position: a good quality telescope in Southern Africa is required as part of the receiver network. HartRAO is in a unique position to take part in these collaborations.

HartRAO also has a collaborative programme with the University of Manchester (UK), HartRAO monitoring the radio emission of stars with circumstellar shells whilst the Manchester astronomers (Jodrell bank) determine the angular size of the shells. SAAO astronomers collaborate in monitoring these stars in the infrared.

8.1.3 Astronomy at Gamma Ray Wavelengths

Gamma ray astronomy is carried out by the Physics department of the University of Potchefstroom, using their own telescope array which detects the Cerenkov radiation generated by extraterrestrial gamma rays as they pass through the atmosphere. The first subunit of a new (Mk II) telescope is already in operation. The principal aim of this work is to detect and study celestial gamma ray sources. there is joint optical and gamma-ray observations of possible sources by the Potchefstroom group and the SAAO.

8.1.4 Theory (including Theoretical Cosmology)

A number of university groups are active in astrophysics and theoretical cosmology. There has been a limited amount of interchange between the observational and theoretical sides in the past, and this could profitably be extended.

8.1.5 International Facilities

While we have had many overseas astronomers come here, conversely astronomers in SA have (as is the custom in the subject) made use of a number of international facilities for their research programmes (e.g. CTIO, AAO telescopes, the IUE and ROSAT satellites).

8.2 The Case for Astronomical Research in SA

While astronomy has had some important practical spin-off (mainly in the development of very sensitive infra-red detectors), its primary justification is as a pure science, studied for its own sake: such investigation of the universe and our place in it, is one of the grandest intellectual enterprises that humanity that can undertake.

The basic case for continuing and developing astronomical research in South Africa can be put as follows:

a) Astronomy is an exciting and important field of physical science to which South African astronomers are making and can continue to make unique and important contributions if suitably equipped. The main need is a 3.5-4m class optical telescope (see below).

b) Astronomy attracts world-class scientists to South Africa, either permanently or temporarily, and thus stimulates general scientific development here.

c) Astronomy enables strong links to be developed with the international scientific community, and enhances the external perception of the country. The status of SA in the field is recognised by high-level participation in international bodies; for example Prof M Feast (SAAO and UCT) has been Vice-President of the IAU (the International Astronomical Union) and Prof G Ellis (UCT) has been President of GRG (the International Society of General Relativity and Gravitation), both bodies functioning under the umbrella of IUPAP (the International Union of Pure and Applied Physics).

d) Astronomy attracts new technology to the country. (A current example is the tests now being carried out at the SAAO by their infrared experts in collaboration with Japanese astronomers on a prototype of a new infrared detector developed in Japan. This array has considerable promise).

e) Astronomy can be used at all levels to impart an understanding of what science is about, and to help establish a broad scientific culture in this country (indeed Planetaria, such as the one at the SA Museum, can play an important part here). This is essential if science is to receive the sympathy and support that is needed for its success here. It seems unlikely that astronomy can be used successfully in this way unless at its heart there is a strong group carrying out research on some of the major astronomical problems of the day.

f) Astronomy has a strong potential for overlapping with, and stimulating, other sciences. For example: in Physics, equations of state at very high temperature and pressures (pulsar observations); particle interactions at very high energies and the nature of 'dark matter' (observations of the large scale structure of the universe). In Chemistry, the formation of complex molecules in space. In the Biosciences, the origin of life (the search for extraterrestrial planetary systems and intelligence). In Geology: the formation of the solar system.

g) Astronomy has a potential to stimulate interesting research and development at the university level in engineering. This is particularly the case with electronics, where there has already been some limited interaction to develop advanced instrumentation for astronomy. This is a field which might develop and be expanded to other branches of engineering. Interactions with industry might follow, but the opportunities are likely to be far more limited.

h) Theoretical work in astronomy and cosmology has a unique place in helping understand the nature of the universe. We can take part in that endeavour at little expense.

i) From the international viewpoint, the SA contribution is important because of its location. There is no other Southern African country doing astronomy; but from the viewpoint of world astronomy, there is a need for telescopes in this region. SA has the expertise and interest in becoming the hub of astronomical development in Africa as a whole.

Overall, astronomy in SA is a highly successful discipline. It makes good sense to support and maintain such already successful science.

8.3 Future Research Needs

The needs of SA astronomy were considered by a committee set up in 1988 by the FRD and representing all areas of astronomical work in South Africa. This committee reported that ".. the needs of the [radio astronomy and gamma ray] fields could be met in the short term by relatively modest expansion ... In optical astronomy on the other hand the Committee agreed that the situation was reaching a crisis point. Unless decisions are made now for major optical instrumentation developments, we shall find a dramatic drop in the status of South Africa in international astronomy in a few years time ... The committee is unanimously of the view that with a telescope in the 3 to 4 metre class, South Africa could look forward to a bright future [in astronomy]".

In November 1989 a *Review of South African Astronomical Observatories* was carried out for the FRD by two distinguished British astronomers. The section of their report headed *Summary* is (in full) as follows:

(i) Both observatories (i.e. SAAO and HartRAO) have a high standing internationally. Their healthy programmes are well adapted both to geography and to current staff levels. Both observatories take part in substantial international collaborations.

(ii) Top priority is the acquisition of a 3.5-4m telescope. International collaboration would thereby be maintained and the international standing of South Africa would be enhanced.

(iii) Support of HartRAO should be maintained with modest upgrading of equipment.

(iv) More vigorous interactions between the observatories and the universities should be stimulated, to the benefit of both.

8.3.1 Organisation

As regards organisation, two points seem clear.

(1) The basic equipment for astronomy is in general expensive and requires expert staff. Thus, whilst not precluding individual initiatives such as the gamma-ray astronomy at Potchefstroom, the pattern of national facilities as at HartRAO and SAAO would seem to be favoured. These national facilities have the added advantage that they bring together astronomers from institutions where they may be working in isolation.

(2) The present staffs of the two national observatories are strongly oriented in their background and general approach to science and to research. Perhaps the main difference between them and astronomers at universities is that they are able to contemplate larger projects which may take many years to complete. Any organisational changes that are made in the future should aim at strengthening the university link whilst leaving the facilities available to all universities in the country as well as to the international community.

8.4 Policy and Priorities

SA cannot afford to take part in some of the big international astronomy projects that are now under way, and will take place in the next decades (many of which are based on satellite experiments). However, we have a valuable resource in our current astronomical research groups and facilities, which should be retained for the reasons cited above. They give very good value for a relatively modest expenditure. In particular, SAAO is a valuable facility that enables us to exploit our Southern position in astronomy, and make a valuable contribution to knowledge.

As has been explained above, there is a need for a new optical telescope in order to maintain our research standing; a detailed analysis of the case for such a telescope, and the associated costs, is given in Stobie *et al* (1993). This would be a cost-effective but expensive undertaking, costing of the order of R90m (spread over 5 years), and would be difficult to finance from SA sources alone. Thus it would be important to make it a shared international facility if possible, enabling sharing of costs with other countries. This would be a continuation of the tradition of international collaboration in astronomy, already well-established at Sutherland. Indeed we can now expect more international interest in placing large telescopes in Southern Africa (e.g. there is current interest from Germany to put a 3.5m telescope in Namibia, and Russians to put a 2.5m telescope at Sutherland).

It is also important to keep up to date with modern detector technology on the one hand, and computer systems, with relevant applications software (data handling and analysis, image processing, perhaps neural networks), on the other. This is where there can be a good interaction with physics, electronic engineering, and perhaps computer science.

On the theoretical side, the observational effort should be supported by small but good quality research groups, with a better link to the observatories than there has been in the past.

Astronomy is an excellent vehicle for instilling an understanding and appreciation of science. Thus initiatives should be taken to have astronomy available as a subject in the secondary school curriculum. This has the potential to interest children in scientific ideas, and channel more children into physical sciences as a whole.

Chapter 9

Physics

Physics is the study of the fundamental properties of matter: its motions, constitution, and interactions, and the transformations between different kinds of matter and energy. It is the foundation of astrophysics, physical geography, chemistry, molecular biology, and all the branches of engineering, and hence underlies all industry and environmental processes as well as all forms of life.

It is this that gives physics its fundamental importance: it is the foundation of the other natural sciences, earth sciences, and life sciences, and indeed of the behaviour of all the matter in the world around us. In particular, it is the basis of modern technology and production processes, and of environmental science. Especially important is the role physics plays as the basis of the accurate measurement and imaging processes which are the foundation of most of modern science (e.g. astronomy, molecular biology), modern medicine (ultra-sound, CAT scanner and NMR imaging), and technological progress (e.g. in fabricating integrated circuits).

Research into *fundamental physics* studies Newtonian mechanics, quantum mechanics, relativity, electromagnetism, thermodynamics and statistical mechanics, particle physics and fundamental forces. The main branches of *non-fundamental physics* are atomic physics, nuclear physics, cryogenics (low temperature physics), plasma physics, condensed matter and solid state physics, optics, acoustics, and space physics (which includes upper-atmosphere studies). Together, these are the bases of applied physics.

Theoretical physics studies the mathematical structures and interrelationships of these various subjects (for example, examining how non-fundamental physics is grounded in fundamental physics), giving better understanding of their natures. The goal of theoretical physics is to find unified descriptions of previously disparate aspects of the behaviour of matter (as for example when electricity and magnetism turned out to be different aspects of electromagnetism), with the ultimate dream of finding one unified fundamental theory that describes the behaviour of all particles and forces.

9.1 Current Position

We have a broad strength in physics research in SA, with particular strengths in some areas and good contacts with overseas researchers in particular fields. This is recognised by our participation in IUPAP (the International Union of Pure and Applied Physics), where H Moraal (Potch) is the new Chairman of the Commission on Cosmic Rays, M Hellberg (UND) is Secretary of the Commission on Plasma Physics, and R Seretlo (Fort Hare) and D MacLachlan (Wits) have been elected members of the Commissions on Physics for Development and on Low Temperature Physics respectively.

Among the areas in which research currently takes place are the following:

9.1.1 Solid State Physics

We have considerable strength in experimental and theoretical solid state physics, which leads in to the important topics of semiconductors and superconductivity. Techniques used include Rutherford backscattering, X-ray diffraction, nuclear microprobe, and transmission electron diffraction. There are applications in microelectronics, materials engineering, thin film superconductors, novel semi-conductor devices, and diamond research. The area is basic to materials science (see below).

9.1.2 Modern Optics

There are active research groups at several universities, investigating laser physics, laser spectroscopy, non-linear optics and fibre optics. Research development is also carried out at the CSIR and AEC. Optics, holography, and spectroscopy are the basis of many analytic and diagnostic techniques, and widespread use is made of these techniques in medicine, communication, environmental monitoring, engineering, and industry. There is significant industrial activity in the design and fabrication of optical fibres and specialised optical components and instruments.

9.1.3 Experimental Nuclear Physics

Experimental nuclear physics in South Africa is now mainly based at the National Accelerator Centre (NAC) at Faure near Cape Town, but with a group also at the Schonland Research Centre for Nuclear Sciences at WITS. At Faure there is the recently commissioned separated sector cyclotron which produces 200 MeV protons, which is unique in Africa. Soon a new injector cyclotron will enhance the capacity of the facility, with the provision of a wide range of heavy ions and also polarised protons. Applications includes radiotherapy (with high energy neutrons as well as protons), radiobiology, nuclear medicine, radiation detection (monitoring and surveillance), and applied nuclear technology. However this work is controversial because of the very high cost of running NAC (discussed in more detail below).

Also at Faure is a 5.5 MeV pulsed van de Graaff (single-ended) accelerator which is no longer used for nuclear physics, but which is used in a variety of applications in nuclear analysis in solid state physics/chemistry and other fields. Recently a scanning proton microprobe was commissioned using the van de Graaff beam.

The University of Pretoria houses a 2.5 MeV single-ended van de Graaff accelerator which is used exclusively for materials science research. The pulsed, single-ended van de Graaff accelerator at the Atomic Energy Corporation at Pelindaba near Pretoria is no longer used for nuclear physics nor on a continuous basis. In an on-demand mode, it is occasionally used for nuclear analysis of materials of interest to the AEC programmes, and is also available on a rent-a-beam basis.

A major accelerator facility, also unique in Africa, is in heavy use in forefront fields at the Schonland Research Centre for Nuclear Sciences in the University of the Witwatersrand, namely a Tandem van de Graaff accelerator with capability of protons-to-heavy-ions production, as also pulsed protons and (through recoil implantation) pulsed heavy ions. This powerful facility is used for a nuclear physics heavy ion research programme, as also research programmes in materials science and nuclear analysis in general stretching from atmospheric problems to biological (e.g. Parkinson's disease) to wide band gap semi-conductors to minerals physics. Important in the approach of the Schonland accelerator group is not to limit itself to analysis for analysis sake, but to take it into dynamic areas of materials interrogation through time-dependent studies emphasizing short time-windows not accessible to other techniques, and to the exploitation of the specific features of ion channeling. The Schonland group pioneered the development of the scanning proton microprobe in South Africa and have extended this in a unique way to scanning heavy ion microprobe capability with enormous advantages. This group is also the first to develop a scanning transmission ion microprobe, also with channeling capability. The Tandem accelerator is the only accelerator in South Africa capable of accelerator mass spectrometry, the need for which is evident from the impact of this technique throughout the world. In South Africa, the Schonland group may be considered as the pioneers of 'minerals physics'.

9.1.4 Experimental Plasma Physics

Experimental work in this area - one of the bases of fusion-power research - has recently been scaled down. However it has resulted recently in interesting developments in gas lenses with applications in gas telescopy and focusing of laser beams to drill holes.

9.1.5 Space Physics

We have an internationally recognised expertise in space physics. Some work is carried out in this area on the solar-terrestrial interaction, including upper atmosphere research, partly in the context of the Antarctic research station (which is well-placed to investigate the ozone hole in the earth's atmosphere).

Our location and the fact that ground-based space physics can be carried out cheaply give us quite an advantage -

(i) the fact that much of the physics of space depends on the earth's dipole magnetic field means that the Antarctic base can 'see' out to a number of earth radii without our having to provide our own satellites;

(ii) our proximity to and activity in Antarctica makes us members of an international activity, giving access at little cost to satellite and other data from others, e.g. (a) we get satellite ozone data from NASA which is relevant to Southern Africa and (b) Walker/Stoker are setting up an HF radar, the cost of which is being shared with the UK and USA, and which will be part of an international network, i.e. there is excellent financial gearing! The data from the SHARE radar will be combined with that from a similar radar at the British Antarctic Base, Halley, to provide information about electric fields, velocities and irregularities in the upper atmosphere over a large region of the Antarctic continent. Sanae Base is ideally located for this experiment. The field of view available overlaps the Halley field of view and covers a region of about four million square kilometres centred on the American base at South Pole.

(iii) we are also geographically close to the South Atlantic Geomagnetic Anomaly, a fact which the Potch group has exploited.

Now it is true that most of the ozone hole measurements are made by satellite, but nevertheless ground based observations play an important role.

Satellite observations are made at a fixed local time - the local time changing only slowly as the orbit precesses. So that those familiar ozone hole pictures are rather more complicated than most people imagine, in that they are built up (giving geographic coverage) over 24 hours at a given local time. By contrast ground observations though also measuring total column ozone give coverage in local time during the day (i.e. sunlight periods). So it may be said that ground observations complement satellite observations and indeed are used to calibrate satellite observations. This point is of course valid for all high inclination satellite versus ground based observations. Also the ground based measurements of ozone give information on ozone below clouds, and more accurate information in the range 9-15 km (but this accounts for only a small proportion of the total column density).

Spin-offs from space research of this type include development of manpower with, for instance, a good understanding of time-series analysis (a valuable tool in many applications), computing, electronics and electromagnetics and of course, the link of space studies to environmental issues. Nowadays satellites play a major role in our lives - communications, TV broadcasts, imaging of the earth and its natural resources, etc. These satellites are ‘ships sailing in the sea of geospace.’ Thus a good understanding of our geospace environment is important to mankind in the future.

9.1.6 Theoretical Physics

We have considerable strength in this area, particularly in theoretical particle physics, studying subjects such as the phase transition between a quark-gluon plasma and hadron gas in heavy ion collisions and in the early universe, and relativistic quantum field theory at finite temperature.

9.1.7 Physics Education

This is a growing area of research, involving physics curriculum development and evaluation, teaching and problem solving methodologies, and language issues in connection with students from disadvantaged backgrounds. It has important applications in science teacher education, and education of disadvantaged students.

9.2 The National Accelerator Centre (NAC)

NAC is used by a wide variety of scientists from different parts of the country. It is amongst the best in the world in a very narrow field of nuclear physics, and will remain useful (if expensive) in that field for at least 10 years. Much of its beam time is used for radiation therapy experimentation; this is innovative work, but the number of patients who benefit at present is small in medical terms. However it is important to have in SA a group of nuclear scientists to exploit nuclear techniques and materials, for a multitude of applications in medicine, industry, agriculture, and radiation safety. It can be suggested that NAC is justified as the basic and applied nuclear research centre of the country. We do not however need a nuclear reactor industry as previously proposed by the AEC. Research at NAC is a mix of physics, chemistry, material sciences, biology, and medical research, and development there involves computer science, electrical and electronics engineering, thus providing a base of strength and knowledge in these areas. It also plays a useful role in training young scientists (including those who need nuclear physics skills).

According to the NAC annual reports, each year about 6500 useful hours - i.e. up and running - are obtained on the cyclotron, and the percentage of total time available and its associated use on the cyclotron for the past three years are as follows:

	1992	1991	1990
Physical Sciences	49	48	45
Isotope Production	26	26	31
Neutron Therapy	15	15	14
Radiobiology and Biophysics	8	10	9

Thus the largest users are physicists, with isotope production second and neutron therapy third.

On the positive side (Lindsay 1993), NAC can be seen as an example of rationalisation which allows many scientists and universities - including some of the Historically Black Universities - to co-operate and use advanced equipment (e.g. 8 UWC MSc's and one PhD; 32 UCT PhD or MSc degrees over 5 years, making a very important contribution to the Academic Support Programme). Thus as well as being an important basic research facility, it is an example of cooperation between different universities and medical research groups in the country:

a) The van de Graaff research is active in solid state and atomic physics, and is for example also useful in geoscience work.

b) The open sector cyclotron is used for basic nuclear physics research by UCT, UDW, Stellenbosch, UWC, Wits.

c) The cyclotron is also used for medicine and biology:
- Treatment of cancer patients (neutron treatment and proton therapy); NAC is the only centre in the world to offer both high-energy neutron and proton therapy, and work there has pioneered innovative methods of positioning patients for brain tumour therapy;
- Production of isotopes, used as a diagnostic tool in many hospitals around the country as required for a proper treatment of a wide range of diseases. Some of the isotopes produced can be imported but at a large cost; some would be unobtainable due to their short half-life.
- Radio-biology: research into effects of radiation on biological material.

d) Accelerator physics: NAC is the base of the only major accelerator physics group in SA, who built the cyclotron and now are responsible for the successful running of the machine. It provides experience in advanced infrastructure; modern electronics, data handling techniques, computer facilities and computer expertise; electronics workshop; library facilities. Thus it plays an important role in training skilled manpower.

It is claimed that NAC is the best utilised research instrument in the country, having run 24 hours per day, seven days per week, for the past 7 years. Its working week of 168 hours contrasts sharply with the normal 40 hours and should be taken into account when running costs are compared.

On the negative side, it is relatively expensive: In 1992/3, the van de

Graaff accelerator laboratory (used by 75 collaborators and 32 research students) cost R2.1m, and the split-sector cyclotron (used by 68 collaborators and 32 research students in the physical sciences, and 37 collaborators and 11 students in biophysical sciences and radiotherapy, also serving hundreds of cancer patients and many thousands of nuclear medicine patients each year) cost R27.5m, while income from sale of radio-isotopes was R670,000 (FRD 1993). Thus its cost was about the same as the whole of the FRD core programme (R29m in the same year). Salaries account for over 50% of the NAC budget (this includes security, gardeners, cleaners, building maintenance), and the budget includes all supporting services, insurances, taxes, levies, library, electricity (nearly R3m a year) [Dr. Reitmann comments that FRD core programmes support university staff whose salaries, overheads, and complete infrastructure are usually provided by universities]. However assuming the necessity of the isotope production and radio-therapy research, the savings that would be made by terminating experimental nuclear physics activity at NAC is only about R1m a year (the cyclotron still has to be run over the weekend - magnetic fields on, rf on, internal beam on - in order to be ready for the doctors at the start of the week).

The van de Graaff accelerator is not cheap but it is good value; in particular it is used for experimental solid state physics, which is of considerable importance (as explained below).

The cyclotron - while of high quality, and producing substantial benefit - is relatively expensive 'big science' for a country of this size. The nuclear physics research produced is good, but cannot be classified as of such major importance that the facility should be kept going at all costs. The medical research is innovative, and the nuclear training role is significant. Furthermore the claim it is expensive needs qualification: it is cheap compared to the AEC budget, and various third world countries - Brazil, Argentina, India - all have cyclotrons as well.

Much of the use of NAC is medical. According to the Chairman of the MRC, the MRC would not itself have invested in a NAC and is, in view of present priorities and circumstances, not likely to change this view. However as the NAC is there, running extremely well and available for cutting edge research in medicine, especially in the very new field of proton therapy, the MRC is using this facility to the best of its ability. The facility provides among the best beams in the world with ample beam time provided, and is the most reliable of all the NACs. Even more important, the wavelength and Bragg peak qualities of the beam are unique and give us an opportunity to make unique contributions in this field. Furthermore the presence of a large number of patients with a large variety of tumour types, often in stages not seen in other countries, provide unique needs and opportunities for understanding.

The cost of NAC is assigned to the FRD budget, although the decision of how much money to spend on NAC is not an FRD decision; the FRD receives special earmarked and entrenched Treasury funding for running NAC and all its activities (including medical applications). If the bulk of the money were allocated through the Medical Research Council, the Department of Mineral and Energy Affairs, and/or the Atomic Energy Commission, and only the marginal cost of the physics were assigned to the FRD, the picture from the viewpoint of *science* funding would be entirely different. However neither the MRC nor AEC would fund these activities unless it received the necessary funds from Treasury.

The IDRC report (1992) criticises the cost of NAC in return for the benefit gained. Nevertheless it is a resource of quality to the scientific community, providing important training opportunities. We will not be able to participate in nuclear physics research collaborations overseas if we do not have a 'home-base' such as NAC. If it were closed down, then over a decade or so nuclear research expertise in the country would dry up, and an important centre of training for physics students will be lost; and the money allocated to NAC would probably be lost to science. Furthermore, the facility is already here; not using it to the full means a considerable loss of money already spent and presently giving benefit.

9.2.1 Assessment

The NAC cyclotron is a well-engineered, indeed "gold-plated" facility, in the design and construction of which no money was spared. In the technical quality of the facility it is at least equal to the best of its class in the world, in other words the energy and particle range which it is competent to cover. The field of nuclear physics which it addresses is however one that has been interrogated for many years, albeit with less-perfect accelerators. Necessarily there remain many questions of detail that can be addressed, and which lead themselves to meticulous research or measurement, that is eminently publishable in leading journals. Herein lies the dilemma: is such research work, even if well carried out, truly justified in terms of the cost thereof, is it worthwhile, is it significant let alone of major importance in terms of the advancement of the overall field of nuclear physics? It must be matter of some concern, for example, that the powerful phalanx of theoretical nuclear physicists in South Africa has not enthusiastically devoted any significant portion of its attention to research in physics accessible to experimentalists using the NAC cyclotron.

It is argued (correctly) that the cost of running the NAC cyclotron facility should not be laid exclusively at the door of the South African nuclear physicists, who as a group are the largest users of net accelerator hours, because the medical component is in fact a substantial user. This is obviously true, but is undermined by the deliberate judgment of the Medical Research Council not to use its own funds for this purpose: indeed the MRC have declared that if they were given funding commensurate with their pro-rata usage of the NAC cyclotron, they would not direct such funds to this end as they had many research needs in their mission substantially of higher priority. Starkly then, if access to the NAC cyclotron is free, the MRC is quite happy to endorse the medical/clinical work, but they quite evidently do not consider it sufficiently important to use their own money to these ends.

It may be argued, again correctly, that it is important in SA to have a group of scientists capable of exploiting nuclear techniques and materials - this is undoubtedly true, but it is far from evident that this is uniquely a NAC capability, indeed a number of South African Universities might well argue that they are at least as competent in this regard. NAC and at least one other "nuclear centre", but possibly more, can justifiably argue that they are the custodians of such nuclear-related skills, but it is not a strong argument in justifying the NAC budget, for example.

It has been argued that NAC is justified as the basic and applied nuclear research centre in the country. This is simply not true in these oversimplified terms: the role of the (user) universities is vital in this regard, the more particularly if collaborative use of the most advanced leading nuclear facilities overseas is taken into account.

NAC does represent a base of strength and knowledge in many areas, but the incisive and possibly harshly pertinent question that may and, in fairness to all, should be asked, is whether it in fact does provide, or is uniquely capable of providing this base. The answer must be obvious: it is not on this basis that it should be attempted to justify the existence of NAC: stronger arguments should be found.

It is fairly argued that NAC represents a resource, in particular, for the nearby universities and technikons. The technikons appear to have made little, or even no, use of NAC facilities, hence in the cold light of reality it is the effective use of NAC facilities by such Universities that needs to be assessed. In such an assessment there needs to be appreciated that NAC consists for these considerations of two facilities, the separated sector cyclotron and the van de Graaff accelerator. Of the latter there is no doubt that it has historically been a (southern) universities resource, and remains so, albeit possibly to a lesser extent. It should be appreciated also that the van der Graaff is now dedicated to solid state and atomic physics and to analysis, no longer to nuclear physics. Although it would be more proper to seek to properly quantify such issues, there would seem to be little doubt that the "output" of the van de Graaff in terms of graduating students and papers published justifies its existence and the commensurate financial investment. It is far from obvious however that the same is true of the separated sector cyclotron: again though not rigorously quantified it is evident that the nuclear physics output in terms of papers published and students graduated is very low, without even taking into account the capital and running costs of only this aspect of the operation. This is the more tragic as it may well be claimed by the SA Institute of Physics that in their document to the FRD under the title "The state of nuclear physics in South Africa" they clearly anticipated this situation, which document in its detail would appear to have been largely ignored.

The question has been raised as to who are the prime beneficiaries of the products of NAC: is for example the Atomic Energy Corporation one such and should it therefore carry a meaningful part of the cost of NAC? The answer is unambiguous: the AEC is most unlikely to claim to be a beneficiary of the NAC "nuclear physics" product(s), and even less likely to see that it has an obligation to support NAC to any significant scale financially, if at all. There are, in respect to the "nuclear physics" aspects of the NAC mission, no other apparent major beneficiaries of the NAC "product".

Where do we go from here with NAC and nuclear physics in South Africa?

There is little point in being devious on this matter: it was a mistake to build the open sector cyclotron - but this fact is now of historic interest only. The NAC cyclotron(s) are a reality, they have been well-designed, well engineered, and the operation is well managed under the present director (who has announced his decision to retire at the end of 1994).

The view of the official NAC Board is sound: though good work remains possible in nuclear physics and in neutron therapy, it is only in proton therapy that any truly significant research importance would seem to lie. Hence it follows that the judgment of the Director to restrict beam-time allocation to nuclear physics to weekends, is sound, with prime week-day time allocated to medical applications and to isotope production. The pragmatic situation is that as long as the present equivalent-Rand budget is granted, the NAC open sector cyclotron should continue to be operated with the current structure of beam-time allocations, but with an in-depth, meaningful review by international experts of the value and impact of what has been achieved in research being undertaken. This is consistent also with the recommendations of the Council of the SA Institute of Physics in their document "The State and Future of Nuclear Physics in South Africa".

What if questions are raised on the wisdom of maintaining the present Rand budget (by direct Treasury grant) attributable to the NAC cyclotron operation? Many questions must then be justifiably addressed: inter alia, can NAC really justify the employment of 228 members of staff? Is South Africa getting adequate scientific value-for-money out of this investment? Would not the expenditure of a fraction of the NAC budget on for example the Schonland Tandem van de Graaff accelerator operation produce more returns in the interests of South Africa, serving as a proven base also for many significant international collaborations?

The saga of NAC and its right to ongoing support on anything approximating the present scale represents perhaps the most significant challenge to wisdom and integrity in science policy in the "new" South Africa. What seems to be required is that an innovative solution should be developed, making the best of the situation we have. A very tentative proposal is given below.

9.3 Why is Physics Research Important?

It is essential for this country to maintain and indeed increase its output of physics graduates, because without properly trained physics graduates, it is impossible to run a modern economy. Thus perhaps the most important single reason for supporting physics is that a physics training is the underlying basis of engineering.

High-tech engineering has a strong basis in physics; thus it is important for our competitiveness to be involved in research that uses modern techniques, e.g. lasers, electronics, communications. Such topics are thus particularly important in the training of research students. We need not only people who can invent, design and manufacture goods that can be sold in this country and overseas, but also people who can adapt imported technology to local circumstances. This demands both technological aptitude and know-how and a research attitude and training. Furthermore, environmental studies has a strong physics component.

Without physics research, one cannot educate a single PhD, MSc or BSc(Hons) Physics students to a level that is comparable to an overseas graduate. Without these graduates, we cannot educate our Physics students up to BSc level because we would not be able to man our tutorials and practicals, which are essential for physics education. These tutors and demonstrators will be even more important with the expected increase in underprepared students in physics. Moreover this is the only way of increasing the number of properly trained science teachers at schools which the country badly needs.

Thus the case for maintaining physics research in the more applied areas, both for the direct benefit in terms of understanding practical issues and in terms of provide research training in these areas, is overwhelming. There is also a good case for supporting limited work in the area of theoretical and fundamental physics, both for its own sake (as in the case of pure mathematics and astronomy), and for the excellent research training these studies provide.

9.4 Priorities

There should continue to be support for a broad spectrum of research activities in physics, as at present. To a certain extent one can claim that it is irrelevant in which field a physics PhD student graduates, because a physicist at this level will have done research in various fields and will be trained to re-analyse any given problem from scratch, searching for innovative solutions to long-standing problems that have been overlooked by people who follow well-trodden paths. A modern economy can only win by having as many physicists as possible, as long as their training has been excellent. Thus if the research is outstanding and not too expensive, and it serves the goal of producing these quality physics graduates, any research group should be financially supported with high priority.

Nevertheless, given this approach, there is a case for steering physics research to a considerable degree towards the applied end of the scale, which is closest to practical applications. A particular area that should be considered here is solid-state physics, which is presently strong and can bear on the economy, particularly as part of a concerted approach to materials science (see below). Modern optics is another significant area, as is the broad field of electronics and communications (which overlap to a considerable degree with electrical engineering and information technology). Finally high priority should be given to projects that develop measurement and imaging techniques, for these are the foundations of investigation and discovery in all areas of science. In all these cases collaboration of universities and technikons with industry should be encouraged, and research spending by industry supported by financial incentives.

There is a case for taking part in international cooperation in basic space science, continuing work already under way, and perhaps opening up room for collaboration with other countries in Africa which have shown an interest in this area. However this need cannot be met by the Denel satellites, which are not aimed at this kind of work. Rather, there is a place for space science if including links into international satellite programmes. Space research benefits from the fact that we are close to the Antarctic, and much relatively cheap ground-based space physics can be done at these latitudes. Furthermore we are close to the ozone hole, and the South Atlantic magnetic anomaly is just off our coast. We should continue research in these topics, seen as a significant contribution to understanding climate and weather.

As discussed above, the cost of keeping NAC going is problematic. A search for other contributors to its cost, other uses of the facility within physics, and ways of saving costs, would make it more attractive. Evaluation of the options needs to take into account the importance of providing research opportunities at a high level to physics students; NAC is an existing successful way of providing such experience, but is not the only option; some proposals are made below.

As in the case of mathematics and astronomy, there is a good case for keeping some high-quality research going in the theoretical areas of the subject, both for its own sake and because profound insights in theoretical understanding are actually the most transforming factors in physics (cf. quantum theory and relativity, both with major practical implications).

Finally research into physics education is a vital and important area that needs to be pursued with vigour (cf. Grayson 1992). The need arises regarding all levels from pre-primary to tertiary.

9.4.1 NAC Again

Physics research is enhanced by major research tools such as the NAC van de Graaff accelerator and cyclotron, discussed above; the question of affordability is paramount here. While desirable in many ways (see e.g. Smith and Bohm 1994), the cyclotron will have to be evaluated against other ways of providing experience in advanced physics techniques (for example, in the context of solid state physics research).

What seems to be requires is an innovative solution should be developed, something like along the following lines:

(a) the van de Graaff should be kept going more or less as is, but with more user-friendly software.

(b) The money allocated to the cyclotron by Treasury should be clearly separated from the FRD budget, as "the NAC's cyclotron receives *no money at all* from the FRD budget" (Dr. Reitmann); costs should be reduced by a variety of means:

- reducing administrative expenditure,
- selling more radio-isotopes,
- persuading user University departments or other entities (the AEC or MRC?) to contribute to costs,
- persuading some other countries to come in and share the cost - for example, making it an African facility, providing training in nuclear physics and accelerator techniques for all countries in Southern and Central Africa,
- possibly considering reduction of annual running time, if absolutely necessary.

(c) Using the reallocated money towards a major thrust to develop solid state physics and materials science as an integrated venture, involving also chemistry as a major component (cf. the following section). The idea would be that this development - much needed in its own right - could in the future be the basis of training of many more physics students in the Western Cape area as well as the Transvaal. Furthermore some of the time NAC technicians presently devote to the cyclotron could be devoted to this solid state physics programme, so that there need be no loss of work for the technicians through money saved by cost-cutting measures associated with the cyclotron. This would probably mean reduction of medical applications that depend on running the cyclotron; this would be an inevitable result of the fact that despite its being a shared facility, it is not a high priority for the MRC or the hospital services.

It must be emphasized that this is a very tentative proposal towards a constructive resolution of the problem presented by NAC, and is not based on detailed study, which could only be made good by a specialist committee set up to look at creative solutions of all kinds. However Dr. Reitmann comments that a string of specialist committees *have* been set up by the FRD to look for such solutions, and have been unable to come up with any major changes in NAC's role or operation: "Like in all other countries with similar facilities, a large accelerator is expensive to run and must be funded mainly by Treasury" (private communication). This appears to put the decision in very bleak terms: to keep it running as is, or to close it down. In the future situation facing this country, it is unlikely that Treasury will consider funding NAC at the present scale, given that it is not a top MRC priority. Thus it must be hoped that serious cost-saving is indeed practicable.

9.5 Equipment

The essential need is for state of the art measuring equipment of many kinds, that are fundamental not only to physics but also to many other branches of science. These are items such as the various kinds of electron microscope, electron microprobes, X-ray diffractometers, spectrometers, and so on. They have to be supported by sufficient computing power, adequately provided by modern work stations in most cases.

It is essential that money be committed to keeping such equipment available and up to date (Pouris and Pouris 1993). They can however be shared across Departments that use them (which include Physics, Chemistry, Geology, Botany, Archaeology, Mechanical Engineering) and between institutions. The need here is for a rational plan of location and use of such instruments, in and between institutions.

Chapter 10

Chemistry

Chemistry is the study of the material world at the molecular level. All of the substances in our daily experience comprise chemical elements or compounds and assemblies of these substances. Chemistry is therefore concerned with the molecular structure and properties of matter and with the understanding of the dynamics of their interconversion and the formation of new substances.

The knowledge base in chemistry is reflected by many millions of chemical compounds which are found in nature or which have been created synthetically. This knowledge base is currently growing by hundreds of thousands of compounds annually. The chemistry of nature and of natural processes has provided the historical inspiration for the growth and development of the discipline. Many familiar processes in our daily experience, such as combustion, corrosion, cooking and fermentation entail chemical change. Additionally, the familiar manifestation of life processes are governed by chemical reactions and interactions and molecular properties and reactions thus provide the foundation of the molecular biological principles underlying zoology, botany and the medical sciences.

The chemical industry has evolved into one of the major wealth generation sectors of industrialised nations, in response to societal needs for the end products of chemical processes. These products are ubiquitous and contribute toward energy production, food, agriculture and health products, as well as a host of fabricated materials. Chemical processes are essential in paper, fibre and textile manufacture, in exploitation and beneficiation of minerals, and in water and environmental science.

The traditional branches of chemistry which are physical, inorganic, organic and analytical have become increasingly interdependent and also pervade the molecular aspects of other sciences. We regard geochemistry and biochemistry as separate topics, considered elsewhere. Organic chemistry is the basis of polymer chemistry, which we regard as part of materials science.

10.1 Current Position

SA has active groups in each of the major subdisciplines of chemistry, based mainly in the Universities, although research chemists are also employed at statutory organisations such as CSIR and Mintek in support of multidisciplinary programmes. The major chemical industries (e.g. AECI, SASOL) also employ substantial research and development teams.

The current status of chemical research in SA may be seen against the background of recent restructuring in certain statutory organisations, most notably the CSIR, where the disestablishment of the National Chemical Research Laboratory in 1987 brought to an end a 40-year period during which NCRL research programmes in the long-term national interest provided opportunities for graduate employment in research, manpower training, and the development of research infrastructure and resources. The absence of this facility has placed more onus on the universities to develop in-house infrastructure and instrumentation for advanced research techniques, and to identify and develop emerging areas of chemical research.

Notwithstanding the setbacks associated with the termination of national services and the loss of momentum in certain areas of collaborative research, the well-established Departments of Chemistry with pre-existing strengths have been able to respond to the challenge of building up in-house resources and strengthening post-graduate training. At the same time, SA chemists continue to play a prominent role in international affairs of chemistry through service on expert Commissions of the International Union of Pure and Applied Chemistry and participation in international scientific collaboration.

The areas in which local research activity continues to impact upon the progress of chemistry are conveniently delineated in the traditional subdisciplines as follows.

10.1.1 Physical Chemistry

This is the most fundamental branch of chemistry, and it deals with the application of the laws of physics to complex chemical problems. Of particular importance is the study of thermodynamics, which is concerned with the energetics of chemical reactions and is directly applicable to chemical engineering. The kinetics and molecular dynamics of complex reactions is seminal to the study of catalysis and finds applications in many industries in South Africa. Modern physical chemistry is heavily dependent on quantum theory which ultimately explains the results of spectroscopy, a major tool of modern structure determination. More recently, crystallography and solid state chemistry have grown considerably in importance, particularly as related to the study of the properties of new materials.

10.1.2 Inorganic Chemistry

Inorganic research plays a central role in the exploitation and beneficiation of fossil fuels and minerals. For example, the energy efficient production of fuel and chemical feedstocks from coal, crude petroleum, and light hydrocarbons is dependent upon catalytic processes, an area in which inorganic chemists continue to make important contributions towards improvements in cost effectiveness of the local chemical industry.

Research is conducted into advanced principles of heterogeneous and homogeneous catalysis and organometallic chemistry, in particular of the platinum group metals which find wide application in industrial processes. Catalysts also play an important and increasing role in the control of environmental pollution and in efforts to functionalise and thereby beneficiate small chemically unreactive molecules, for example carbon dioxide and simple hydrocarbons which contribute towards industrial wastage of biomass and long-term environmental hazards.

Attendant studies into inorganic reaction equilibria and kinetics and into the molecular structure and properties of organometallic complexes, ionophores and metal clusters are targeted towards the development of new generation catalysts, selective agents for separation science, the synthesis of diagnostic and medical agents, and the ingredients for advanced materials.

10.1.3 Organic Chemistry

The historical development and growth of organic chemistry, through the isolation and structural elucidation of natural products is reflected in the pioneering research which has been conducted in South Africa into the identification of active components in poisonous plants and organisms and of materials used in traditional medicine. Research in these areas continues to receive attention with an increasing focus on chemosystematics, structure-activity relationships and the exploitation of natural products as chiral building blocks in the synthesis of industrial intermediates and end products.

The development and application of synthetic methodology are central features of current research into the rational design of complex organic molecules, biomimetic processes and catalysis, and enantioselectivity in total and partial synthesis. Attendant studies on reaction mechanisms provide insight into the role of structure and conformation upon molecular properties and reactivity. These investigations are essential to the development of insight and experimental skills which can be applied to the development of new products and processes in industry, examples of which include new generation medicinal and agrochemical agents, advanced industrial catalysts based on biomimetic principles, and the design of biodegradable ingredients in everyday industrial and household chemicals.

10.1.4 Analytical Chemistry

Analytical chemistry studies the determination of the chemical composition of any substance and thus pervades all branches of chemistry, and its applications are wide ranging and form the basis of subjects such as geochemistry, chemical oceanography and environmental chemistry. Thus expertise in analytical chemistry is the basis of all chemical research and its industrial applications. Recent important analytical techniques include mass spectroscopy, gas chromatography, high pressure liquid chromatography, electrochemical methods and thermal analysis. All of these are widely used in industry, and many university graduates and technikon diplomates are employed as analysts in a wide range of industrial activities.

10.2 The Case for Chemical Research

Chemistry is an eminently practical science since molecular properties and phenomena influence every aspect of our daily lives. At the most practical level chemical research provides the essential underpinning of a major sector of the manufacturing and processing industry, which confers benefits on every conceivable aspects of material welfare in modern society.

The SA chemical industry is heavily orientated towards the exploitation and beneficiation of local coal derived feedstocks and minerals, as well as imported petrochemical feedstocks for the manufacture of fuels, lubricants, solvents, fertilisers, polymers, explosives, surfactants and related industrial chemicals. An important but hitherto less developed sector of the industry is devoted to manufacture of more advanced commodity chemicals and fine chemicals. The future growth of this vitally important industrial sector will rely increasingly upon the ability to produce higher value-added end products competitively, for import replacement and possible export.

Examples of areas of current opportunity include research into improved catalysts and catalytic processes, beneficiation of secondary products and the development of processes and products which diminish environmental hazards. Although the expected impact of research into fine chemical processes and products is likely to be longer term, the growth of local and regional demand should provide future opportunities for more local manufacture of pharmaceutical agents, agrochemicals and related products.

These developments are critically dependent upon investment in research and development and in improved facilities for advanced training of graduate chemists. In order to achieve and retain international competitiveness in a research-dependent chemical industry, it will be necessary to train more chemists to Ph D level and to ensure that standards of teaching and research conform to international norms. The South African industry is well positioned to take advantage of feedstocks and of the growing regional demand for chemical products and processes, but it will require imaginative investment in the increasingly expensive instruments and facilities of chemical research to achieve the desired results.

The case for chemical research is also manifested by the central role which it plays in integrated research, for example in complementary studies involving the organic chemistry and biochemistry of biological processes. New insights into the molecular bases of substrate-receptor interaction hold the prospect of designing target specific compounds for therapeutic purposes. Similar principles are expected to find application in new-generation agrochemicals for improvement of crops and pest control. Chemistry also constitutes an essential element in the multidisciplinary studies devoted to understanding and controlling the environment. Threats to the quality of the environment demand rigorous monitoring through advanced analytical techniques, in order to determine the impact of population growth and industrial development upon essential resources such as water. The role of analytical chemistry in the exploitation and beneficiation of mineral resources and in material sciences also continues to pose research challenges.

In order to maximise the material benefits of chemistry to society, it is also necessary to ensure that aspects of fundamental chemical research remain vigorous. The basic principles underlying molecular properties and reactivity continue to contribute toward important practical advances in the subject.

10.3 Policy and Priorities

Continued support for training and research of all the interdependent disciplines of chemistry is an essential prerequisite for the inevitable growth in demand for chemical services and products which will accompany population growth and increased industrialisation and urbanisation.

There is a need to identify and strengthen those areas of chemistry which are likely to maximise societal benefits, in particular, improved chemical production technologies, higher value-added chemical products, and chemistry targeted at production of food and health products. In addition, the role of chemistry in integrated areas such as biotechnology, materials science and the environment should be nurtured.

The respective roles of the universities and the technikons in these endeavours are complementary, and their contributions toward advanced training and research will benefit from industrial support for collaborative undertakings.

Every effort will need to be made to ensure that good students undertake postgraduate training, in preparation for the more demanding challenges which confront the chemical profession in future.

It is questionable whether a prescriptive policy for chemical research priorities is necessary or desirable, but the research community will need to take advantage of unique regional opportunities and needs in order to secure ongoing support for its efforts. Some of these are exemplified.

10.3.1 Catalysis

The design and application of catalysts for chemical transformations is a familiar and important feature of the SA chemical industry, and the ongoing challenge to achieve higher levels of conversion efficiency and to develop environmentally benign chemical processes continue to offer research opportunities. Several research groups are active in this area, and benefit from collaboration with industry, This activity can be expected to continue and to provide a basis for developing and applying new principles in catalyst design and catalysis.

Catalysis research should continue to make an impact upon research into more effective utilisation of local fossil fuel resources as chemical feedstocks rather than as primary sources of energy, In addition, SA is the major producer of the platinum group of metals which feature prominently in a huge and growing area of chemical catalysis, and provide regional opportunities for value addition through further research into the chemistry and properties of derived organometallic compounds.

The current effort and investment in catalysis research should be sustained, and can be profitably extended into some of the specialised areas which are on the international forefront of future-directed research. These include the design and synthesis of biomimetic catalysts for chemoselective and enantioselective transformations,and the principles and applications of supramolecular chemistry.

10.3.2 Organic Synthesis

Organic synthesis is the corner-stone of the modern fine chemicals industry, and a major area of wealth generation in industrialised nations. The future prosperity and competitiveness of the SA chemical industry may well depend upon its ability to identify and develop selected opportunities for fine chemicals production. This, in turn, will demand high levels of creativity and experimental skill from its practitioners, a challenge to which the SA university community is well able to respond. At present, aspects of research into organic synthesis are being conducted at most SA universities. Some of this work has received international acclaim and provides outstanding training for graduate students, who can be expected to influence the course of future industrial research and development in their eventual places of employment.

Two distinctive aspects of organic synthesis can be identified. The first entails development and application of new methodology for synthetic transformations, and offers good opportunities for short-term benefits. Typically, this will provide entries to improved process technology for end products of known utility, as well as the opportunity for development and application of enantioselective processes to value-added chiral intermediates.

The second and arguably more challenging and rewarding area of organic synthesis is synthetic design and attendant partial or total synthesis of new end products. This includes structural modification of natural products in order to modify properties or bioavailability, as well as synthesis of targets identified by predictive design principles. At present, limited opportunities can be foreseen for application of this approach, in the local chemistry industry. The risks are high and there is a need for a long-term multidisciplinary effort to identify and synthesize targets, and then to conduct appropriate follow-up studies. However, the skills developed in programmes of this nature can readily be adapted to more readily attainable goals.

Research programmes in these areas are vitally important for manpower development as well as possible spin-off benefits, and can provide stimulus to develop new enterprises based upon custom synthesis of advanced organic intermediates and specialities.

10.3.3 Natural Products Research

The rich biodiversity of SA flora has long provided unique opportunities for natural products research. Pioneering studies in the past have focused mainly on chemotaxonomy, and the active principles of toxic plants and traditional medicines. Although major scientific discoveries have emanated form this work, there is an urgent need to update systematic documentation in this area, and to coordinate integrated inter-subject research into potentially useful products. The organic chemist is only one of the contributors to this effort, but the task of isolating, purifying, and determining the molecular structure of natural products is the essential factor in making meaningful progress in natural products research.

It is recognised that natural products research world-wide is sometimes poorly conceived and indifferently executed. Without reliable data on the claimed bioassays, for example, of plant material used in traditional medicine, and reliable bioassay methodology to monitor isolation and purification procedures, it would be futile to undertake a major programme in this area. The challenge to SA natural products chemists will be to seek inter-subject collaboration, in order to identify those research opportunities which have appropriate regional advantages in terms of access to plant material and possibly utility of products arising from the research. It will be equally important to establish reliable bioassay methodology, and mechanisms for possible medicinal applications and commercial follow-up.

An attendant opportunity in this area will be to pursue international collaborations, particularly within Africa where natural products research is widely practiced. Local skills and resources could thus be used to foster regional cooperation in areas targeted at mutual interests in human health, agrochemistry, and possible economic development. Informal contacts have already established the scope for such collaboration, and the time is clearly ripe to initiate facilitating mechanisms for implementation of joint programmes.

10.3.4 Environmental Chemistry

Rapid population growth, urbanisation, and industrial development continue to exact a toll upon the SA environment, most notably in terms of the quality of the atmosphere and water, and the accumulation of harmful residues in the food chain. In the face of socio-economic priorities in SA, the lessons of the heavily industrialised nations will need to be assimilated and applied as a matter of urgency if we are to avoid or ameliorate some of the more dire consequences of environmental degradation.

Analytical chemistry occupies a central role in industrial processing and in the attendant measurement and interpretation of its consequences upon the environment. This discipline will continue to grow in importance in the foreseeable future, and will provide rich opportunities for the development and application of new methods for rapid and accurate quantification of the effects of human activity upon the environment. Again, this is a multi-disciplinary area but,since many of the factors which impact on the environment arise from chemical substances and chemistry-related activity, the role of the analytical chemist in environmental research is essential. SA has a long tradition of achievement in the analytical sciences, arising to a large extent from the expertise built up around the mining industry, and can be expected to meet the future research challenges in environmental chemistry, given the appropriate support in equipment and advanced training.

10.4 Equipment

Modern chemical sciences have become totally reliant upon advanced instrumental techniques in probing molecular structure and in analysing and separating chemical components of complex mixtures. No modern laboratory can stay abreast of developments without access to an array of sophisticated instruments such as high-field nuclear magnetic resonance and mass spectrometers and X-ray diffractometers, in addition to the more conventional instruments for routine analysis.

It would be impractical to expect every institution practising chemical research to acquire all the necessary instrumentation for up-to-date research and teaching. Accordingly, it can be expected that there will be a growing demand for such facilities to be concentrated in those centres which can ensure a high level of usage and which can sustain the infrastructure to offer regional and national services. The dearth of such services following the termination of the former role of the CSIR in this area has placed smaller university chemistry departments at a severe and growing disadvantage as graduate training centres.

Additional needs in chemistry research include consumable resources many of which are imported at great expense, and state- of-the-art information retrieval services which continue to suffer from diminishing university budgets for this purpose.

Chapter 11

Materials Science

Materials Science: The systematic study of matter in bulk, unifying the disciplines of *metallurgy* , *polymer science* , *ceramic science*, and *solid-state physics*, using *techniques* such as crystallography, electron microscopy, and x-ray diffraction, in an attempt to understand materials such as reinforced and pre-stressed concrete, metallic alloys, polymers and composites, and ceramics, and to develop useful new materials such as carbon fibres.

This is an integrated field of endeavour, building on strengths in physics, chemistry, and engineering, with strong links to economic opportunities. It is one of the fields identified by the USA scientific advisor Dr. Bromley as showing great promise for the future in the world market (cf. Scientific American 1986), and is one where SA is reasonably well placed to carry out good research that can help establish a sector of our local industry on a solid foundation.

11.1 The Case for Materials Science Research

SA has major reserves of many valuable minerals, and the energy resources needed to exploit them. The need to improve the balance of trade by exporting the products rather as finished goods or advanced materials rather than as ores or as crude metals has been generally recognised. As far back as the 1950's the CSIR recognised the need for a strong school of solid state physics which would support industry, and planned that it would be established on the Witwatersrand, the hub of mining and metallurgical industries. Since that time there have been two important developments world wide. The first has been the increasing breadth and sophistication of solid state physics, which resulted in part of the field developing strong links with parts of metallurgy and of chemistry to form the new subject of materials science, with the related applications in materials engineering. The second has been the realisation in recent years, especially in the USA, that the development of materials science has been rather one-sided, perhaps because of its roots in solid-state physics.

There is a strong and widespread knowledge on the side of materials characterisation, the relation between the microstructure of a material and its properties. There is much less understanding and very much less dissemination of the science of materials processing, the science or art of creating the desired microstructure. This is a field in which SA, aiming to progress from being a producer of ores to a producer of useful materials, has both a need and an opportunity to strive for scientific leadership. As an example, a major need of SA is mass housing. This will require roofing, bathroom furnishings, water and sewage reticulation. The best materials for some of these needs may well be fibre-reinforced plastics. The design of structures based on these anisotropic materials and the technology of their manufacture are still far from full development. Here, SA could hope to have a place in the forefront of technological advance, based on local economic needs and on locally available raw materials.

The Columbus stainless steel project is founded on local raw materials and is placed to satisfy a local market. It may at present use established technologies, but it is large enough to develop in new directions. SA is still the centre of the world trade in gem-quality and industrial diamonds, and maintains a major laboratory for diamond research (although this area of endeavour is vulnerable to fluctuations in demand).

Another example is the use of solar energy. While SA is likely to make a minor rather than a major contribution to the basic development of solar cells, the integration of these into systems that could provide radio, TV and modest electric lighting to the huge population of SA that is out of range of the electricity grid involves scientific and technological problems which are best solved in SA, and are based on the properties of materials.

While its remoteness from the world's major economic centres is usually detrimental to the economy of SA, this possibility of supplying the products of technology to Southern Africa illustrates that remoteness can also bring economic benefits. There are other examples of the benefits of remoteness. SA already has a substantial activity in the air travel industry, and in the repair and maintenance of aircraft. The latter involves a high and steadily developing level of materials technology, which can be developed further. The long-established ship repair industry is similarly based on South Africa's geographic position, and is based on materials technology.

From a broader point of view, solid state physics and materials science provide a useful bridge between the aspirations of the 'pure' scientist who just wants to know how Nature works, and the 'applied' scientist who wants his work to be of social or economic benefit. Even if they extend to the scale of high-resolution electron microscopy or large computers, the resources required are modest, in comparison with those required for other leading branches of physics. The results can be striking, whether they bear on fundamental problems in quantum mechanics as in the fractional Hall effect or possibly on direct economic applications, as in high-temperature superconductivity.

11.2 Policy and Priorities

We have established research strengths in the fields of materials science, which enables us to take part in one of the major new economic opportunities opening up. There should in the future be a major effort in materials science research into minerals and other materials that we can produce, studying their properties, and - through that - their applications. This should include direct research related to mineral beneficiation, which could also have an important economic effect. However the broad programme should also include a component of basic research on materials, to provide a solid foundation for long-term developments in the area. The programme should be undertaken both at Universities and Technikons, and in industry, in a collaborative venture.

There has in recent years been a concentration on the physics of semiconductors. It could be useful to examine whether, in view of the strong centres in this field in some of the most economically developed countries and the ready transportability of the products, this emphasis is still likely to be productive. Some of the other areas mentioned above should be considered for development, for example reinforced plastics and composite materials, together with associated surface engineering and new processing techniques.

In a very useful analysis propounding the opportunities offered to us in materials science and engineering (Nabarro, 1994), F R Nabarro suggests solid-state and materials science requires smaller and more diverse equipment than nuclear physics; so there may be a case for perhaps three centres across the country, specialising in different areas within the broad field of solid-state physics, materials science and materials engineering (for example, with groups specialising in surface science and polymer science).

11.3 Equipment

The effort will depend on availability of state-of-the art equipment of the kind mentioned above (see the Physics section). However even on the few-million rand scale of major electron microscopes and computers, the expenditures tax the very limited resources of SA. Planning is needed to ensure that the country gets at least one first rate experimental facility and maintains established centres of materials excellence.

A comprehensive programme involving basic theoretical as well as experimental could require considerable computing power, to enable development of theoretical models of materials.

C: Life Sciences

The life sciences cover on the one hand the study of plants (botany) and on the other the study of animals (zoology), including humans. The physical, chemical, and molecular foundations of life are studied in biophysics, biochemistry, and various disciplines which incorporate molecular biology, e.g. microbiology.

We have included Archaeology and Palaeo-Anthropology in the life sciences because of their close relation to evolutionary theory and their common methods with palaeontology. However we have not included general ecology, regarding this as part of the integrated area of environmental studies (ecology has important botanical and zoological components, but also has important components from other subjects - specifically physics, chemistry, geology, soil science, and meteorology).

SA biological research in the terrestrial environment of the African subcontinent embraces aspects of almost all the disciplines and sub-disciplines. It has achieved considerable quality, and has broken new ground in some areas involving technological innovation and refinement. This is exemplified by the leading international body of experts and expertise that SA has developed in the field of practical wild-life management, including treatment of diseases, translocation of wild animals, etc. Another example is SA's advanced fresh-water treatment technology, based on bacterial systems. Less applied but still practically oriented in the sense that it aims at yielding results for management, is SA research dealing with the functioning of such ecosystems as fynbos, savanna, and Karoo. This has been carried on in depth, and aspects of this research have won international acclaim.

The sections that follow are, 8: Botany, 9: Zoology, 10: Microbiology, Biochemistry, and Biophysics, 11: Archaeology and Palaeo-Anthropology.

Chapter 12

Botany

Botany: The scientific study of plants (including trees, algae, fungi, and weeds). Botanists seek to understand the structure, physiological functioning, embryological development, evolution, and classification of plants. Applied botanists study the factors that control the germination, growth, and form of plants in order to improve their cultivation and utility.

Botany is the foundation of agriculture and of botanical ecology (the understanding of the development and function of vegetation in our natural environment). This is fundamentally important because all life depends for its existence on plant life. Botany is also important in understanding the evolution of life, and is the foundation of horticulture and plant conservation. SA has a particularly significant role to play here, because of its great natural wealth in flowers (for example, the Cape Floral Kingdom - occurring naturally only in the southern and western Cape - is one of the six recognised floral kingdoms in the world).

The major branches of Botany are Plant Taxonomy, Physiology (including plant biochemistry, molecular biology, and pathology), Plant Ecology, Ethnobotany, and Plant Genetics and Evolution (including Paleaobotany, the study of plant fossils). Specialisation may take place in terms of studying different types of plants: crop plants, trees, flowering plants, aquatic plants, algae, fungae, weeds, or pollens; or in studying plants in particular environments: for example desert, mountains, Savannah, tundra, lakes, the sea.

Botany has the most direct interaction with its applied siblings, Forestry and Agriculture. It has very strong links with Zoology, sharing many concepts and some methods. Other closely associated disciplines include Biochemistry, Microbiology, Chemistry, Geology, and Archaeology. Botany also forms part of the general grouping of Environmental and Geographical Sciences.

12.1 The Nature of Botany

Botany has its origins in the use of plants in everyday human living for food, shelter, and medicine. These practical concerns remain central to the discipline today, though its applications have become fragmented into applied sub-disciplines such as agriculture and forestry. Modern botany probably dates from Linnaeus' grand project to systematically catalogue all the plants on earth in the 18th century.

Darwin provided a secular mechanism for the creation of biological diversity with his theory of evolution by natural selection. He had a great interest in plants and was a keen experimentalist, laying the foundation for many 20th century scientific concerns. However Darwin lacked a credible hypothesis for inheritance of traits from generation to generation. Mendel discovered the particulate nature of inheritance from studies of plants. The rediscovery of his work at the beginning of this century provided the foundation for genetics, the science to which we probably owe most for keeping one step ahead of famine despite exploding human populations.

12.2 Present Botany in SA

SA has a strong botanical tradition and good research groups, however there are also substantial gaps in what is being done at present. In this section we consider the major branches of Botany and their present status in SA.

12.2.1 The Classification of Plants

Plant *Systematics* is the science of the diversity of plants, in turn the foundation of *Taxonomy*: the classification of all living things (each placed in a kingdom, phylum, class, order, family, genus, and species, wherever possible this classification being based on structural or evolutionary rather than behavioural characteristics).

Systematics is extremely important as the foundation on which all other biological sciences depend (Bruton 1989): it is the basis for conservation of biodiversity, and of identification of horticultural plants, crop plants, weeds, and those that are poisonous or are of use for pharmaceutical substances or manufacturing (Reid and Archer 1993).

South Africa has a very large flora, nearly 10% of the world's flowering plant species, and 80% of these are confined to the region. Floristically, at least, we are quite distinct from the rest of Africa. A large and vigorous community of botanists are involved in cataloguing and classifying these species. The field has been invigorated by the introduction of analytical tools - cladistics - which are intended to reconstruct the evolutionary history of a group of species, and has the potential to revolutionise systematics, providing a clear logical foundation and transparent methods for reconstructing phylogenetic history. As a result, systematics has become increasingly absorbed in tracing the history of taxonomic units, using formal quantitative methods.

However it remains a controversial technique, for its ability to reproduce synthesized genealogies is limited; it is restricted to simple, discretely coded data whereas most characters are polygenic, variable and overlapping between taxa; its group structures are over-simplified; and its computational procedures involve subjective choices of method and can only examine a limited proportion of possible genealogies when more than about 15 to 20 species are being analysed. Thus more promising cladistic-like methods are being developed to fulfill this promise.

Another important growth area is the use of molecular methods to provide new characters for classification. These new thrusts have tended to replace the interest in process (e.g. the workings of natural selection in populations) which drove systematics in the first half century.

The basic home of taxonomy is museums and Herbaria, which house the major collections and can provide identification of specimens. For example, the Bolus Herbarium at UCT has an all-hours service to assist medical practitioners with identifications and with guidance on the literature of toxic substances. It also provides a specimen collection for rapid and efficient identification of plants for use by environmental impact assessors, conservation groups, and landowners

12.2.2 Evolution and Genetics

Systematics deals primarily with the products of evolution. Studies of the process itself have been somewhat neglected in South Africa. Thus there have been very few studies of how plant populations change across landscapes and under different environmental conditions, and whether such changes are genetically based. These intraspecific differences are of considerable academic interest but they are also of major importance in applied breeding programmes. Plant breeding is not taught in most Botany Departments and is also not well supported in agricultural faculties in this country. This is a serious deficiency in training, given the enormous importance of plant breeding in feeding, clothing, and sheltering the worlds billions. Horticultural development of the flora has also been neglected. Conventional plant breeding has lost ground to molecular biology, which ultimately promises greater precision in manipulating traits by genetic engineering. However until this promise is realised sometime in the future, it would be prudent to develop a much stronger indigenous conventional programme in plant breeding.

An important aspect in the study of evolutionary history is the study of extinctions – indeed evolution and extinction are partnered but different processes that are vital in shaping the world's biota.

12.2.3 Palaeobotany

Palaeobotany attempts to reconstruct vegetation of the past. Palaeobotany has undergone a renaissance in the last twenty years, and has lead palaeobiology in the reconstruction of ancient ecologies. Besides the intrinsic interest of exploring the past, palaeobiology has also been used to explore the consequences of contemporary global changes such as the greenhouse effect and the rapidity of change under changing climates. SA has a very active group of researchers studying vegetation change as a means of assessing the extent, rate and direction of environmental changeover the last 10 to 60000 years from pollen and other data sources. These studies are closely allied to archaeological investigations of human evolution. Only a small body of researchers studies the more ancient past, despite the rich macrofossil flora of the Karoo beds.

12.2.4 Evolutionary Ecology

Evolutionary ecology explores the relationship between form and function as the outcome of natural selection and other evolutionary processes. Despite promising beginnings, for example by Bews, Marloth and others in the 1920s, these studies languished in South Africa until recently. The rich South African flora, especially the Cape flora and the succulent Karoo, provide remarkable opportunities for comparative studies of form and function. There is increasing interest in this field, especially in the south-western Cape. Biologists have become fascinated by the amazing diversity of flower types and their sexual systems, their intimate relationships with pollinators, the unusually high number of ant-dispersed fynbos species, the diversity of responses to fire, and the intriguing question of how plants avoid being eaten by herbivores. Physiological studies have explored the implications of different vegetative structures. Studies in this sub-discipline form the substance of natural history studies used in television or newspaper features for entertainment and education. Good natural history studies, disseminated by film or television, are an important attraction for eco-tourists. The new David Attenborough BBC TV series on plant life, with several sequences based on South African research, serves as a potential example.

12.2.5 Plant Ecology

Plant Ecology studies the relationship of plants to their organic and inorganic environment. Plant ecology in South Africa has two major sub-disciplines. One, known as phytosociology, studies patterns of plant assemblages and their relationship to climate and soils. Plants are sensitive indicators of environmental conditions, and maps derived from phytosociological studies provide an essential database for land use planning. The vegetation of the entire country was classified into "veld types" and mapped in the 1950s by J. Acocks, long before such exercises became common in other parts of the world. Acocks veld type maps have had a profound impact on agriculture and conservation in South Africa and continue to be updated and extended.

The second major thrust of ecology has been in understanding the causes of vegetation change - plant succession. These studies were begun in the 1920s by JFV Phillips who was a world leader in the field. Our detailed understanding of Knysna forest dynamics, perhaps the most intensively managed forests in the southern hemisphere, stems from his work. Since most management of semi-natural vegetation involves manipulating succession for particular objectives, successional studies provide the conceptual basis for veld management. SA has been in the forefront of applied studies of plant succession in grasslands and savannahs. More recently botanists have also made major contributions to the dynamics of Mediterranean type shrublands, from studies of Cape fynbos. These studies of vegetation dynamics are used in managing vegetation for livestock production, conservation, harvesting of indigenous plant products, and forestry.

New directions in ecology come from the realisation that global changes in climate and atmospheric chemistry could fundamentally alter plant distribution or local abundance. As yet studies of the impact of CO2 increases, UV radiation, air pollution and global warming are in their infancy in South Africa.

12.2.6 Physiology and Phytochemistry

Physiology and phytochemistry study the plant as machine. Their scope varies from studies of the relationship between plants and their environment (ecophysiology), to the inner workings of the cell and its biochemistry, to molecular studies of the workings of genes and their impact on whole plants.

To feed the burgeoning population of South Africa, agricultural productivity is going to have to increase three-fold in the near future. This will have to occur in a country where the majority of land is marginal for intensive production. Increased productivity will have to involve the development of both improved production techniques and new varieties that are either high yielding, or more tolerant to the stresses imposed by more marginal land. An understanding of plant response to stress implies that studies on natural flora can have important applied aspects. Whether these new varieties are produced by conventional breeding techniques, or by modern genetic transformation processes, an understanding of determinants of growth and resistance to stress is essential. No attempts to improve agricultural productivity will succeed without a sound plant physiological input.

A further threat facing this country is habitat degradation and loss of genetic resources. This could occur both by competition for limited land resources and by over-exploitation of current natural populations of utilised plant species. Any proposal to conserve these resources must be based on a knowledge of the environmental interactions, regeneration characteristics, and growth processes of the important plant species involved. A basic understanding of the physiology of a far larger proportion of our indigenous flora is essential to any proposal concerning the viable utilization and conservation of our natural flora.

The use of molecular biology as a new tool in studying plant genetics, development, and functioning promises to open up entirely new understandings and possibilities in botany. In particular, genetic engineering opens up a new route to development of plants with desired characteristics, for example that are resistant to particular diseases or insects, or that are drought resistant.

Considerable advances have been made in techniques of plant propagation. South Africa has an excellent capability in these methods and is using them to propagate a variety of crops, including rare plants such as Warburgia which are in great demand in the herbal medicine trade, bulb plants of high horticultural value, and clonal varieties of eucalyptus for commercial afforestation. New techniques of plant propagation are a key factor in the rapid advance of biotechnology and underlie much of the spectacular progress in crop improvement over the past decade.

12.2.7 Studies of Particular Types of Plants

Organisms traditionally studied by botanists include the algae, most of which are not related to higher plants, and the fungi, which is certainly a very different group of organisms.

a) The study of *algae* (phycology) is an active discipline in South Africa, particularly with respect to marine macro- and micro-algae (seaweeds and phytoplankton). This is important because of their role at the foundation of the food chain in the sea. Seaweed harvesting is of growing commercial importance in South Africa. Good scientific links have been established with Namibia and East African countries which have an established seaweed industry.

b) Mycology, the study of *fungi,* has tended to be separated into departments of microbiology where increasingly molecular approaches are pursued. Symbioses between higher plants and fungi and nitrogen fixing bacteria are essential for the nutrition of plants and are studied by a small group of specialists in the country.

c) Related is *Plant pathology,* the study of plant diseases, because many are of fungal origin. Following the lead of VanderPlank, South Africa has an excellent reputation in the field which is of great economic significance.

12.2.8 Ethnobotany

Ethnobotany is receiving growing interest throughout the world with the realisation that both traditional knowledge of plant resources and the plants themselves are being rapidly lost. In South Africa, there has been an explosion of scientific interest over the last ten years. Traditional plant uses for medicinal, veterinary, agricultural and other practices are being documented, active compounds investigated and the economics, ecology, exploitation or cultivation of the resources explored.

12.3 Conservation and Restoration

There are two related but important trends in SA today that are of major concern. Both relate to degradation of the botanical environment and loss of our unique plant heritage.

12.3.1 Degradation and Restoration

There has been a continued reduction and deterioration of the quality and cover of vegetation and soil mantle upon which the sustainability of food, fibre and fuel resources depend. This has happened particularly in the 'homeland' areas on the one hand, and the township areas on the other, but is by no means confined to these locations; indeed there is significant degradation on many 'white' farms too. The latter is controversial, and the nature and extent of what is happening is in dispute (in particular the phenomenon of 'desertification' and of extension of the Karoo).

We need first to establish what is in fact happening, and then to look at restoration of these areas and their long-term sustainability, most particularly in the devastated homeland and township areas, but also in the white farming areas. Many socio- economic factors enter, but a crucial element is the botanic one, where for example understanding of the processes at work and the selection or development of suitable species for particular environmental circumstances could play a major role. This is thus an important area of experimentation and research.

12.3.2 Indigenous Flora

We have a unique opportunity, in Africa at least, of melding traditional knowledge of a very rich resource base with sophisticated techniques for developing the resource. There is a growing body of competent black botanists with considerable interest and expertise in collating the shrinking information on traditional plants. There is also a competence in developing sustainable harvesting regimes and in propagating indigenous material (of which Geoff Nichols is one example, others include the successful commercialisation of Scelocarya, the marula). A problem at the moment is the shortage of natural products chemists and poor communication with the medical fraternity when it comes to testing active components. Translating the research into commercial products e.g. packaging of widely used traditional herbs for use in the massive urban markets to help relieve the natural resource base is a major problem.

We have to be aware of the irreversible loss of biodiversity and of its potential benefits to humanity (both in aesthetic terms and in terms of possible use for food, medicines, or other purposes). Apart from flower-pickers, the destruction of plant environments, and invasive species, there is a perceived threat to indigenous flora from two directions: a) export of large quantities of plants to overseas researchers , b) herbalists and related practitioners who utilise plants for medicinal purposes.

As to the first, we should apply similar policy to our flora as to other natural resources. In a practical sense the problem can be tackled by running projects on a collaborative basis, with SA researchers also becoming involved in these investigations. In line with other moves to process raw products before exporting them, we should aim to do initial processing of plants (isolation, separation) here and send the semi-refined extract overseas. We need to consider carefully why we cannot do more about developing these resources ourselves. Careful thought also needs to be given to the large-scale export of plants overseas; if all the institutions concerned with Natural Products research, including commercial companies such as Noristan, could reach a common policy, SA could benefit. For example, in the Natal area all interested persons - organic chemists, botanists, taxonomists, herbarium personnel have met to i) draw up a catalogue (past and future) of natural products research in the province, and ii) formulate some sort of policy with respect to requests for plant material from overseas.

As regards herbalists, many indigenous plants traditionally used in the herbalist trade are now becoming vary rare, others are nearly extinct. In this connection valuable work has been done by Dr. Tony Balfour-Cunningham to draw attention to the subject of ethno-botany. Sterling work has been done by Geoff Nicholls of the Durban Corporation Gardens Department in establishing a large indigenous nursery at Silver Glen, south of Durban. At this commercial nursery herbalists are able to purchase rare plants and bulbs and use them for medicinal purposes. It is clear that restrictive legal measures have had only limited success in protecting endangered species. The survival of these plants requires that they be grown by farmers in suitable areas all over SA, in the same way as any other cash crop.

12.4 The Need for Botanical Research

There is clearly an important need for botanical research as a basis for our economic use of plants and trees on the one hand, and for understanding their role in the environment and ecology on the other, which is the foundation of plans for developing an ecologically sustainable society. These aspects of research need to be tied in to research in Applied Botany: Forestry, agronomy, horticulture, plant breeding for example.

There is also need for more fundamental research in terms of understanding the functioning and ecology of plants and trees, as well as the classification that is the foundation of evolutionary studies and conservation. These are worth doing both for their own sakes and because of the foundations they provide for the more applied research, which cannot be satisfactorily pursued without a base of research in the more fundamental areas. We already have excellent work going on in these topics in this country, so we are well placed to continue that work, albeit with some changes of emphases.

12.5 Policy

The basic need is to continue the work already under way, but with some new emphases. Botany in SA has a reasonable research capacity in many fields, but due to the small size of the community it is extremely fragile. Botany contributes significantly to the First World sector of the economy in fields as diverse as forestry, the deciduous fruit industry, rooibos tea, maize production, horticulture or seaweed harvesting. Scientific capacity in these areas must be maintained at adequate levels, with strong links between the universities and applied research institutes. The kind of project that can have big pay-offs is assessment of techniques for ameliorating the effect of water salinity in crop plants.

Little attention has been paid to applied research in the Third World sector, despite growing interest in ethnobotany and indigenous plant use. We have much to learn, in this respect, from neighbouring countries that have maintained a scientific capacity such as Zimbabwe. However additionally, in common with all science, botany is a vehicle for the pursuit of knowledge for its own sake, and their should be a strand of research of this nature also. This may sound unimportant in view of the social and economic problems facing the country, but such a view is short sighted. A curiosity about the world in which we live is an important component of human nature. If curiosity and intellectual endeavour are stifled, then South Africa will never achieve a respected position in the community of nations.

It may be suggested that particular efforts should be devoted to the following areas.

12.5.1 Taxonomy

There is a need to speed up taxonomy programmes in Africa, particularly in the very species-rich south. There is a need to build up a strong taxonomy of the plant cover of Africa, not only to provide a data base for managing the dominant bio-mass but also to give efficient means of identification so that research programmes on the utilization of ecosystems and species can be properly documented. At present plant identification is far too slow and unwelcoming for plant users. Part of the reason is that taxonomists with the appropriate identification skills are deeply pre-occupied with badly needed revisions of old classifications. Despite many years of work by small teams there are still too many names that have to be changed due to old, information-weak past taxonomic studies, carried out without proper field support for studying variation patterns. Thus there is a need for a programme to increase the rate of progress in taxonomy to make the data bases of systematics more efficiently accessible. The point is that taxonomy is the basic alphabet of biology; without it we cannot communicate the simplest results, let alone the more complex. This work should use modern EDP methods to manage data and information, and to assist with classification and cladistic-type analysis.

12.5.2 Improved Productivity & Restoration Ecology

Primarily, we should concentrate on improving productivity to supply food and shelter (wood products) for all the people in SA. A great deal could be done in homeland areas both in crop improvement and agronomic practise. In townships its more a matter of training in existing gardening techniques, improving supply of seed sources, and creation of the necessary infrastructure, perhaps allotments with a water supply; thus here it is research on the implementation of known botanical ideas that is needed.

Additionally we need to look at restoration and sustainability, most particularly in respect of the devastated homeland and township areas. We should play an active part in the International Sustainable Biosphere initiative, especially in the area of restoration ecology, attending to the rehabilitation of the homelands and many white farming areas. This research would be a good vehicle for collaboration with other countries in Africa.

12.5.3 Ethnobotany

SA has the best documented record of the patterns, processes, and prospects of biological diversity for any country in Africa. But we must take this further in terms of assessment of the potential uses to man of our 22000 taxa of higher plants. We need an energetic national programme for ethnobotany, which must link with international programmes on biodiversity and economic and ethnobotany.

Examples of the kinds of projects that can be carried out are,
* work on commercialising indigenous plants such as the marula, garcinia, strychnos as fruit sources, and others as sources of drugs (the marula project is a good example of a recent success story in tapping an indigenous plant),
* development of guidelines for the sustained use of wild-flower resources,
* investigation of the agricultural potential of invasive plants, for example Acacia thickets,
* investigation of the economic importance of seaweeds,
* investigation of the prospects for agroforestry in SA,
* work to address the huge problem of supplying the urban market with traditional herbal remedies, such as is carried out e.g. at Natal University's Institute of Natural Resources.

12.5.4 Molecular Botany

We should somewhat strengthen our research in molecular botany, because this is the door to programmes in genetic engineering of plants that show great promise of being one of the sources of much improved agriculture in the future.

12.5.5 Informal Sector Research Activity

Botany is one of the areas where on can use the energy of the informal scientific sector, as well as the resources of formal the sector, in research projects. This not only enables projects that would otherwise be impossible, but is an excellent part of science education (see the later discussion on this topic). Accordingly, such topics should be encouraged where they can have real scientific value. A specific excellent example is the Protea Atlas project (see the superb *Protea Atlas Manual* by Antony Rebelo, 1991).

12.6 Research Equipment

All disciplines of botany require some expensive equipment. Plant propagation facilities, including growth chambers (phytotrons) and glasshouses, are essential items for all institutions involved in botanical research and involve a high initial capital cost and relatively high maintenance costs.

Physiological equipment includes many expensive items, some of which are unique to the field (gas exchange equipment), but much of which is shared by other disciplines (electron microscopy, mass spectrometers, chromatography equipment, DNA laboratory material etc.).

Apart from this, a requirement specific to the field of botany is Herbaria, which house botanical specimens and are a fundamental requirement for all botanical studies.

Chapter 13

Zoology

Zoology: The science that deals with the structure, physiology, embryology, evolution, ecology, and classification of animals (including fish, birds, and insects). Human beings are included in this study insofar as they are broadly analysed as part of the animal kingdom, but a more detailed study of humans occurs mainly in medicine and archaeology.

Zoology is the foundation of animal husbandry in farming and veterinary science, as well as of wild life conservation (which is important in much eco-tourism), and plays a major role in the understanding of ecosystems and environmental management, with important applications for example in fisheries. SA has a significant role to play in such research, because of its great natural wealth in animal life. This is true also of Genetics and Evolutionary studies, which are not only fundamental to understanding the historical development of life and in particular of humanity, but also have become the major organising principle of modern biology.

The major branches of zoology are systematics, animal physiology (including molecular zoology), developmental zoology, genetics and evolution, palaeozoology, animal ecology, marine biology, animal behaviour and sociobiology. Specialisation can take place in terms of the type of animal studied: mammals, birds (Ornithology), fishes (Ichthyology), insects (Entomology). However it can also take place in terms of the type of environment studied, for example forests, rocky shores, deep sea, savannah, deserts, Karoo.

Zoology has very strong links with Botany, sharing many concepts and some methods; indeed many of the research concerns are very similar. Other closely associated disciplines include Biochemistry, Microbiology, Chemistry, Geology, Medicine, and Archaeology. Zoology forms part of the general grouping of Environmental and Geographical Sciences, and is a fundamental component of Ecology.

13.1 The Current Position

Zoology in SA has considerable historical strengths: particularly marine biology, since the days of John D Gilchrist at the turn of the century, and palaeontology of the mammal-like reptiles of the Karoo red beds studied by Crompton *et. al.* It has major strengths today, for example we are leaders in the field of ornithology and much marine research is at the cutting edge of science.

13.1.1 Systematics

Zoological Systematics is the science of the diversity of organisms; it is at the roots of zoology and is basic to it. It is the foundation of *taxonomy*: the classification of living things into kingdoms, phyla, classes, orders, families, genera, and species.Ideally this classification is based on evolutionary relationships.

There is an ongoing need to identify and classify animals, without which it becomes impossible to make comparisons and predictions. All classifications are provisional and subject to modification as new information and interpretations become available. The mere accumulation of facts does not constitute the science of taxonomy: these facts must be organised as a predictive model in order to be useful. Thus every biological classification is in fact a scientific theory, for it is a scheme of ordering and relating. Modern classifications use molecular genetics as an important component in determining phylogenetic relationships (taking advantage of the fact that each organism contains a historically evolved genetic programme resulting from millions of years of natural selection).

At the basic level, adequate taxonomic coverage of our biota is a minimum criterion for its management and for the rational development of agriculture, forestry, fisheries, aquaculture, as well as for progress in ecology, genetics, botany, zoology, palaeontology, archaeology, microbiology, and parasitology. At the revisionary and explanatory levels, taxonomy has a massive potential to contribute to the understanding of problems in ecology and evolution.

We are fortunate in having a few good groups working in this area. However coverage is incomplete: for example in the marine field, there is a great need for sponge and ascidian taxonomy, and insect taxonomy, where most of the taxa have not yet been described. There is perhaps a need for greater involvement in the new genetic methods based on molecular biology.

13.1.2 Evolution and Genetics

The study of evolution and genetics is closely related to systematics. Work specifically on animal evolution and genetics has centred in the Transvaal and the S A Museums; because they are central to biology, these topics are dealt with peripherally in a large number of other studies. Animal breeding is treated as an applied topic with little relation to theory, although this could in principle change to some extent with the advent of molecular biology techniques. There is a need for more work on population genetics. As in the case of botany, the study of evolutionary development is partnered by the study of animal extinctions.

Developmental biology (the way the genetic code is implemented to form the embryo and then the animal) is relatively little studied in this country, considering it is one of the most exciting areas of modern research. The main work is concentrated in the Witwatersrand University Zoological Department.

13.1.3 Palaeontology

Strictly, Palaeontology is the science that deals with the fossil remains of both animals (Palaeozoology) and plants (Palaeobotany) found buried in rocks. However in practice Palaeontology commonly refers to the former - the study of animal remains, rather than those of plants, which is distinguished as Palaeobotany (see 12.2.3). Palaeontology forms an important part of evolutionary studies on the one hand and of paleaoclimatology, the study of ancient climates, on the other; this is relevant for understanding present-day long-term weather processes. It has close links with geology and archaeology in terms of aims (study of evolutionary history through precise dating techniques), methods (e.g. radiometric dating), and the fieldwork necessary.

SA has yielded some of the world's most important fossils, indeed 'the familiar dry Karoo has been compared with the seven wonders of the world by a leading United States scientist, because of its abundant and varied wealth of extinct animal remains' (Cluver and Barry 1977). There is a strong tradition in this area through men like Robert Broom and S H Haughton. This work continues today, centred in the Museums and the Bernard Price Institute at Wits; additionally, as in the case of astronomy and botany, SA is a centre to which foreign palaeontologists come because of the richness of its resources. These are particularly important for example in piecing together an understanding of the Permian and Triassic ages.

13.1.4 Ecology and Biome Studies

Animal ecology studies the relationship of animals to each other and to their organic and inorganic environment. As mentioned above, such studies have been carried out in depth in various biome studies (discussed in the ecology section) that are properly regarded as part of the fully integrated study of the ecology of these biomes, rather than just a branch of zoology.

These studies are potentially of importance in determining management policies of natural systems. For example the ecosystem associated with the Benguela current is the basis of SA's West coast fishing industry. Judicious management of this industry will only be possible if the functioning of this natural system is properly understood. It is essential that periods of vulnerability of this ecosystem be predicted if fisheries are to remain a valuable source of protein in the future. The Benguela Ecology Programme (discussed in more detail below) is a highly successful programme studying a viable basis for managing the west coast fishing industry, e.g. anchovy, pilchards, hake, and mackerel. Mathematical models are being developed to serve as a basis for determining optimal harvesting, i.e. for obtaining the maximal catch in a given year that can be taken without harming the production in later years.

13.1.5 Physiology

Physiological studies are usually carried out in the context of particular environments, or types of animals (see next subsection). Such studies are fascinating and instructive in their own right. The physiology of survival in particular contexts, e.g. desert habitats, sandy beaches, rocky shores, or the Antarctic, is of considerable interest in understanding biological adaptations and processes, and is the foundation of the ecologies of those areas.

On the practical side, physiological and toxicological studies are the basis both of veterinary science (and medicine, in the case of humans), and of determining the proper treatment of pollution (for example, through understanding how and to what degree marine pollution affects the physiology and productivity of marine flora and fauna).

Ethical issues can arise in physiological studies, that need careful consideration. That topic is outside the scope of the present document, but must not be ignored.

13.1.6 Animal Behaviour

The study of animal behaviour - for example, that of ants, bees, birds, and many kinds of mammals - is of considerable interest in its own right; in terms of evolutionary theory; and in terms of the light it may help throw on human behaviour. Some studies in this country, for example on baboons, have been of considerable interest. Perhaps most unexpected have been studies by J U M Jarvis of the social behaviour of Naked Mole Rats, showing them to be 'eusocial', i.e. the queen suppresses reproduction in other females and is tended by workers, as in a bee or termite colony. This is the first discovery of eusociality in mammals.

13.2 Studies of Particular Types of Animals

Studies of particular types of animals are often undertaken as part of larger ecological studies. For instance a lot of work has been done on krill and seals, major components of the Southern Ocean and Benguela ecosystems respectively. Equally, taxonomists, who mostly work in museums or university Zoology departments, are usually specialists in a particular group of animals, while many academic zoologists have chosen to work on aspects of the biology of a single group or even single species. More and more emphasis is being placed on biological studies of native animals suitable for aquaculture. These are most frequently freshwater fishes but marine invertebrates such as abalone (perlemoen) and rock lobsters are presently receiving a lot of attention.

Some animal groups are of sufficient interest or economic importance that whole research units are devoted to their study; because of their appeal, and sometimes also for economic reasons, mammals, birds, and fishes are widely studied. Several research units are devoted to study of animals important in relation to health. Much of their work has initially involved detailed taxonomic studies, and, ironically, the primary aim has often been the effective eradication of the species in question (e.g. ticks, freshwater snails, various insect groups including mosquitoes). The great bulk of this work is entomological.

13.2.1 Mammalian Biology

The study of mammals is carried out at universities and museums and by Nature Conservation agencies and agricultural institutes, the last two particularly in the context of farming and wild life studies. The largest concentration of zoologists studying mammalian biology, including the biology of marine animals, is probably at the Mammal Research Institute of the University of Pretoria.

13.2.2 Ornithology

Ornithology is the scientific study of birds, which is carried out largely by nature conservation agencies and universities, and particularly at the Percy Fitzpatrick Institute of Ornithology at UCT (the only ornithological institute in SA). A myriad of biological disciplines have benefited conceptually and practically from the study of birds. Conspicuous among these are animal behaviour, evolution, physiology, population biology, ecology, animal husbandry and conservation biology. Within SA, there are strong bases of expertise in ornithology; a recent survey of the strengths and weaknesses of SA science (Pouris 1989) placed ornithology first among 108 specialities within SA and fourth overall (just behind Canada) internationally.

Given the high priority that environmental conservation has been accorded in South Africa and the enormous economic potential of ecotourism, owing to their popularity with tourists and relative ease of study, scientific information on birds can be of particular value in making conservation-related decisions. For example, an understanding of patterns of distribution, diversity and endemism of birds can be used to prioritise areas for tourism development and conservation action, and the roles birds play as indicators of ecosystem functioning and status can help conservation managers choose when, where and how to intervene in order to optimise the preservation and utilisation of biodiversity (e.g. through commercial hunting and the captive bird trade).

Because of bird migration, ornithology provides links to many far-distant countries, for example Russia and England. It is thus a good field for international cooperation.

13.2.3 Ichthyology

Ichthyology is the study of fishes, economically valuable as a resource for angling and commercial fishing, as well as being biologically interesting in their own right. Major sub-disciplines of ichthyology include the study of fishes of lakes and rivers, estuaries, rocky shores, coastal seas, and the deep ocean. These are of practical significance for the fishing industry (e.g. studies of the food chain in Antarctic waters) and for the conservation of marine resources (e.g. through studies of the role estuaries play in the life-cycles of fish). Good work is being done in these areas, particularly through the Sea Fisheries Research Institute in Cape Town (a governmental institution), and the J L B Institute for Ichthyology at Rhodes University, which is very strong on fish taxonomy and on important applied studies such as aquaculture and mariculture.

The study of fishes is also of great interest in terms of understanding evolution. Work on Lake Malawi fishes and SA Minnows is helping in this regard, as is the painstaking study and classification of southern African fishes.

13.2.4 Entomology

Entomology is the study of insects, which play major roles in ecosystem functioning, which can have devastating effects on crops, and which are vectors of the parasites that cause many of our most serious diseases (mosquitoes are vectors of malaria, fleas of plague, and Tsetse flies of sleeping sickness, for instance). Methods of control of parasites and pests of various kinds, for example wood-boring beetles, locusts, termites, and fly larvae, is an important area of study.

Biological control of plants and pests has been the aim of much research; excellent work has been done in this regard, and has received international recognition. There is a now a move to molecular biological methods of control, made possible by gene cloning.

Limited but good entomological research has carried out in SA, the prominent groups perhaps being those at Onderstepoort and in the Department of Agriculture, but also with some excellent work being done at universities. Given the importance of the subject, it appears that while the quality of the research being carried out is high, the quantity is inadequate. This is an area offering excellent prospects for collaboration with other countries in Africa, e.g. Kenya, and with source countries of invasive plants (mainly Australia).

13.3 Policy and Priorities

The importance of research in zoology is clear from the above discussion, particularly for the management of natural resources and as the foundation of farming and veterinary science. As in the case of botany, there is a need for applied research in the various areas, together with a continuation of fundamental research. That research should have a particular emphasis on those aspects where our fauna provide unique opportunities to us because of our environment. The fields we can study with particular advantage in SA involve studying the interactions of animals with their natural environment and with other organisms, and the practical implications of these findings. There should be,

- research to explain forces influencing biological diversity, and the significance of diversity,
- research on the relationship between community and ecosystem structure and environmental forces,
- research on the response of animal populations and communities to environmental change,
- research on the restoration and/or rehabilitation of ecosystems,
- research on the response of communities/ecosystems to exploitation in the face of environmental variability and change,
- research related to the optimal sustainable use of natural resources, in particular examining novel possibilities such as game domestication and mariculture.

While it is important to examine the individual components of ecosystems (e.g. the physiology and behaviour of particular animals), in the end the important issue is to integrate these studies to understand ecosystems as a whole, as discussed in the section on integrated studies. Such analysis has to be based on local research and local conditions. For example, our understanding and management of oceanic fish stocks must be based on locally derived knowledge of the contiguous Atlantic, Southern and Indo-Pacific Oceans and their faunas, taking into account the circum-polar nature of the southern ocean. We cannot just extrapolate findings from the northern hemisphere, high latitude situations to our southern hemisphere, mid-latitude situation.

As in the case of botany, all the studies have to be based on adequate taxonomy programmes in order that data bases of systematics are efficiently accessible. More work is needed here, particularly in the area of insect taxonomy. Four further points are of importance.

13.3.1 Cooperative Applied Research

There should, as in the previous cases considered above, be an effort to direct a substantial proportion of research toward the applied end of the scale (without losing the basis of 'pure' research that provides the more fundamental understanding). In that applied work, there should be more integration of research in universities and technikons with that done in agricultural research stations. There should also be collaborative work done with local communities, aimed at meeting their needs in an 'appropriate technology' spirit. This requires setting up appropriate consultative mechanisms and suitable research stations in a local setting. For example work to rehabilitate township or homeland ecology requires setting up research stations in those environments; work on optimal resource exploitation requires consultation with the affected communities on their needs and wishes.

Another area that should be encouraged is that of biological control, where we already have an established track record. Given the fact that we have a massive problem with alien plants and that their continued spread threatens water, grazing, and ecotourism resources, further research in this area should be encouraged. This research is extremely cost-effective both in terms of its execution and the products it delivers.

13.3.2 Molecular Biology

The new opportunities opened up by molecular genetics and the methods of molecular biology should be exploited in conjunction with biochemists and biophysicists (see below). This is one of the great new areas of understanding, with potential practical applications that could revolutionise many aspects of applied biology: pest control, parasitology, veterinary medicine to name a few.

However to make good on this promise it is essential to support 'blue sky' research in this area whose immediate application is unclear. This both provides the foundation for the other research, and has the potential to lead to quite unexpected discoveries in this area. The better we understand the fundamental nature of this topic, the better equipped we will be to undertake powerful practical applications.

13.3.3 Informal Sector Activity

As in the case of botany, there is a great opportunity in zoology to encourage informal sector research activity in suitable spheres. Indeed that has already been done in the Southern African Bird Atlas Project (Harrison 1988, 1992, Underhill *et al.* 1990) demonstrating the practicability and utility of this idea in ornithology. This might easily be extended to other areas, for example Entomology.

13.3.4 Palaeontology

We have a unique fossil record in this country, in that we have the largest records of vertebrate palaeontology that spans the reptile to mammal transition. We should accordingly continue at the present level or even extend our work on palaeontology, exploiting this exceptional historical heritage that enables us to make a unique contribution to world knowledge of evolution. This would be facilitated by a rationalisation of palaeontology, at present thinly spread over the country. Thus (de Wit 1993), one might suggest there is a case for creating one main centre of strength in the country for vertebrate palaeontology, invertebrate palaeontology, and even possibly micro- palaeontology. This would need consideration and debate; there could be more suitable forms of rationalisation.

These subjects are of importance in the context of investigating global climate change (see the section on Climatology). They are also of considerable interest in their own right, for example in terms of the light they throw on evolution in general, and the extinction of the dinosaurs in particular.

13.3.5 Ethical Committee

While we have not discussed ethics of animal studies in this document, nevertheless this is an important and emotive topic. A special inter-disciplinary committee should be set up to consider these issues and make decisions on them. This is a difficult area; precisely how to do this, and what policy guidelines to follow, will need considerable public debate and negotiation.

13.4 Equipment

The needs for major equipment to be used in physiological studies are much the same as in botany. However for many studies in zoology there is a need for transport that can be expensive: boats and ships (for the study of marine animals including fish), aircraft (for aerial surveys of animals and for studies of birds), 4-wheel drive vehicles (to reach game areas), satellite remote sensing.

Some research requires housing and keeping animals in good health, requiring adequate premises, cages, food, and environmental control.

Museums are as important for animal systematics as herbaria are for plant systematics (and can also be extremely valuable educational tools).

Chapter 14

Microbiology, Biochemistry, & Biophysics

Microbiology: the study of unicellular organisms (bacteria, fungi, yeast, and viruses) and their functioning. This is of fundamental importance in subjects such as medicine and agriculture because of the ubiquity of microorganisms, leading to important applications for example in food technology, human and industrial waste treatment, and plant and animal pathology.

Microbiologists study microbial systematics, physiology, metabolism, ecology, and evolution, with specialisations focus on the interaction of microorganisms with humans, animals, or plants. Until recently, application was dominated by *fermentation* (bacteria/ yeast), which is still important and indeed is the basis of many industries and natural processes (e.g. digestion). However with the increasing applications of recombinant DNA technology on micro-organisms the focus has changed to genetic interventions and transgenic organisms; thus much modern microbiology centres on *gene cloning* and the related technology of molecular biology. Consequently, we include in this section the two closely related disciplines of Biochemistry and Biophysics, whose concerns and methods overlap with those of microbiology to a great extent.

Biochemistry: The chemistry of living organisms, that is, the nature, functions, and transformations of their molecular constituents such as proteins, nucleic acids, carbohydrates, lipids, and coenzymes. Metabolism includes the processes by which biomolecules are synthesized and broken down and related energy transduction. Cell biology involves the characterisation of different molecular assemblies within living cells, their organisation and dynamic behaviour. Recombinant DNA technology is an important part of modern biochemistry, including chemical DNA synthesis and analysis (sequencing). Biochemical methodologies are fundamental to modern research approaches to most of the life sciences.

Biophysics: the study of living things by physical methods, involving processes of separation, imaging, and irradiation, and the interpretation of their structure and function in physical terms. In particular this includes *molecular biology*: the interpretation of biological structures and performances in molecular terms.

Molecular biology is the basis of modern biotechnology and understanding of how life functions, with enormous implications for the revolutionising of medicine, agriculture, and also perhaps the processing of many materials. Closely related is medical biochemistry (and related subjects such a immunology), not dealt with explicitly in this report because it forms part of the medical sciences.

14.1 The Current Position

Genetics worldwide is today at a crucial stage, being transformed by the massive human genome project and its peripheral satellite programs, such as the exploration of small genomes from extremophiles (high temperature loving, high salt loving microorganisms), the yeast chromosome project, the mouse chromosome project, the rice chromosome project, to name a few. These will supply us with an incredibly large body of new DNA sequence data in the next decades.

The first set of basic results will consist of gene products (proteins) and their allocated genes. So we will be able to compare the principle set of genes for organisms, like plants and animals, animals and humans, humans and yeast, etc., as far as a clear cellular function for the gene is known. We will have to develop techniques to speed up and cut costs as far as sequencing is concerned. The level of precision of data has to be improved. An error rate of 0.1 percent means that in the human genome 3 million bases will be wrongly allocated. And as we have no clue how large the natural variation in certain gene sequences is, it becomes even more crucial to raise the overall precision for the technique.

Another aspect of the sequencing work will be the assessment of horizontal gene transfer across species barriers, e.g. through viruses, which integrate temporarily into one organism and subsequently repackage imprecisely into a virus which can infect another species. An example is mouse leukaemia virus in the cat genome. We will probably encounter more horizontal gene transfer, possibly even autocatalytic gene transfer where a piece of DNA can cut itself out of the genome and reintegrate in to a different genome.

The whole question of how stable the total genome is will come up. The benefit from large scale sequencing will come from the large new database to compare corresponding genes from different species. It will help to identify the molecular origin of human inheritable diseases, as long as they are inherited as a simple Mendelian entity. There is a remote chance to get a hand on the more complex mechanisms of the inheritance of chronic diseases such as scleroses, or even of drug addiction. We have at this stage only a marginal knowledge of control regions in the genome, such as transcription factor binding sites. There may be something to be discovered regarding a folding code to control chromatin structure (in contrast to the classical genetic code).

There is no special SA stronghold in sequencing. But it is foreseeable that in the near future sequencing will be taken over by commercially organized sequencing companies, which could claim sole ownership of any piece of DNA identified as having a specific function.

The second field of progress will be in the understanding of protein stability and function. We are currently unable to design a new protein *ab initio*. The study of proteins from extremophiles will help us understand the rules that nature has developed to adjust to extreme conditions. Knowledge of these rules will allow us to design or improve naturally occurring proteins for application in industrial processes, with a precision of function far beyond that available through the application of enzymes derived from natural sources. It is not inconceivable that SA will contribute to this development at some stage.

Indeed SA has considerable strengths in the areas of microbiology and biochemistry, giving us a sound basis to take part in the very important future developments anticipated in these areas. This level of expertise has received international recognition, as evidenced for example by the fact that Prof D R Woods (UCT) is a member of three International Union of Microbiological Societies (IUMS) Commissions: the Division of Bacteriology, the International Committee on Economics and Applied Microbiology, and the International Commission on Microbial Genetics.

14.1.1 Agriculture

Agriculture is expected to be an important area of application, to make substantial progress in achieving self- sufficiency in food and natural fibre. However increasing population (subsistence agriculture) and commercialisation of agriculture (cash crops) have put enormous pressure on the resources needed for sustained growth in production. Plant improvement by conventional breeding methods is slow, and has consequently to be supplemented by genetic engineering.

It would be favourable to foster close cooperation between Agricultural Research Council laboratories and university departments with a strong record in plant pathology or biotechnology; for example people from promising research labs in the ARC system could be seconded to centres of excellence at universities or suitable sites elsewhere, for training in molecular biology techniques. This is indeed happening at the two leading biotech labs in the ARC, namely Infruitec (Stellenbosch) and VOPI (Roodeplaat, Tvl).

Africa-specific problems must be identified and 'farmer-friendly' solutions identified. It should be kept in mind that the problems of subsistence agriculture of third world peasant farmers are remote from the problems of large scale industrialised farming (first world). Effective and sustainable methods of soil improvement as much as plant disease management are needed in the battle for higher yields. Unwanted microbial competitors and spoilers of food and fibre supply have to be identified, and their life cycles and vectors studied to be able to effectively disable them. Examples are that virus-resistant genes for vegetables and protection of sugar cane from insect borers are under development and already being tested. Maizestreak virus is endemic in Africa - we need to develop resistant cultivars. In many cases this will require a huge amount of basic research - scientists at UCT have been working on MSV for over 8 years and it will probably take at least another 3 years to achieve resistance. It could have been speeded up considerably by increased funding - but it also required new technology along the way, developed internationally but also by the UCT microbiology department.

To achieve the required improvement in the time taken for the needed research, work in the relevant university departments as well as at ARC centres around the country needs to be improved by more manpower and increased funding, particularly encouraging collaborative integrated research by funding priorities. This field has to be multi-disciplined, as it includes biochemists/molecular biologists, plant physiologists, entomologists, plant breeders, etc.

The need to 're-invent the wheel' has to be acknowledged in some cases, e.g. in order to introduce herbicide, virus, bacterial, fungal, or insect resistance into our own crops. This is difficult for degree and publication purposes at universities. It is fine for ARC labs, but they presently have limited expertise. We need funding for technicians working at universities to do much of this developmental work.

All the SA expertise in plant genetic engineering lies in introducing non-plant genes to generate resistance. As much of the plant improvement for yield, drought tolerance etc. will lie in understanding plant molecular biology, we need to invest in this area, and to target it for both teaching and research. It is almost totally disregarded in SA, while it is probably the hottest topic in botany in the USA and Europe, and has great promise for practical applications.

Finally, a field of expertise where SA can match the rest of the world is plant virus research. If the virology can be complemented by adequate facilities for gene analysis, to understand the disease-causing features at the molecular level, it may even be possible to control virus infections in the future, which at present account for about 20% loss in harvest yield.

14.1.2 Industry

A number of industries depend on microorganisms - either naturally occurring or genetically improved. These include mining (use of microorganisms to run refining plants or leach gold out of old minedumps), food and beverage, pharmaceutical, fermentation and waste industries. Research to support these cannot be neglected if we are to remain competitive. In some cases microbiologically based techniques are available that could transform an industry (but their use depends on a change of technology in order to become competitive), or open up entirely new possibilities (e.g. production of lysine for poultry and animal feed).

For instance scientists at the University of Stellenbosch have introduced into yeast genes encoding commercially important enzymes which could improve the clarification of fruit juices (via pectin degradation) and enable brewers yeasts to utilise more of the hydrocarbate present in barley (via starch degradation). In addition microbiologists at the University of the Orange Free State are using yeast for industrial waste disposal and in the production of ethanol.

14.1.3 Human and Animal Medicine

Killer diseases - TB, AIDS, foot and mouth - are important to the entire population. It is important to identify areas where SA scientists can make a major input e.g. developing TB vaccines and AIDS diagnostic kits (but not AIDS vaccines - that is probably beyond us). There are other potentially huge money spinners such as equine 'flu. The ability to understand and implement molecular biology locally is very important in medicine, and the impact of molecular genetics in medicine is potentially huge in the advanced countries.

Firstly, the ability to isolate single cells from the 8-cell stage of an undifferentiated human embryo plus the power of PCR, hybridisation and related techniques in gene amplification and detection, has important implications for medicine and the screening of genetic diseases.

Secondly, as mentioned above, the sequencing of the human genome project is gaining momentum and much faster, automated DNA sequencing techniques are being developed. The end result is the rapid advent of gene therapy which has long been the goal of molecular biologists since the discovery of transduction and the use of bacterial viruses to transfer genes from one bacterium to another. The NIH Recombinant DNA Advisory Committee recently approved human gene therapy experiments involving a potential cure for cystic fibrosis whereby the normal cystic fibrosis gene will be transduced by a 'tamed' harmless cold virus into cells of the pulmonary tract. By using the 'targeted magic transducing bullet' scientists should be able to insert the functional gene into the defective pulmonary tract cells of patients and cure the disease. A single infusion of a vapour containing millions of defective transducing cold viruses could permanently cure a prevalent and awful disease.

Thirdly, the study of the regulation of proteins by ligands: various groups employ a complete integration of molecular genetics and structure and function of the proteins being studied. Protein engineering has been realised and will be increasingly exploited for the design and production of useful proteins.

The attainment of these ultimate goals in molecular biology means that there are tremendous possibilities for SA in the various fields of biotechnology based on molecular genetics; due to our particular demography and ecology, we have many unique situations which are ideal for development of "niche areas" of unique expertise. We have to investigate how best to bring these benefits to this country. Although pioneering at this stage, gene therapy and protein engineering have the potential to become routine procedures available in SA, at first on a limited scale, but eventually for the benefit of all South Africans. As biotechnology becomes a routine part of medicine, agriculture and industry the costs will decrease. It is essential we make the long term investment in education in molecular biology to be able to understand and apply at the local level these types of exciting advances.

14.1.4 Other Areas

Additionally biotechnology will be exploited and become essential for all areas of biology including ecology and taxonomy. The ability to characterise biological phenomena at the molecular level is an exciting and irresistible reality which attracts good students and industrial funding because of the developments in biotechnology affecting agriculture, medicine, and industry. In comparison with many other scientific projects the capital costs of doing molecular biology are relatively inexpensive. The running costs are high but are likely to decrease as the science based on recombinant DNA technology expands. The area is ideal for a collaborative approach involving various scientific disciplines and areas of expertise.

14.1.5 Ethical Consideration

Fundamentally important ethical issues arise in biotechnological applications, that need careful consideration. That topic is outside the scope of the present document, but must not be ignored.

14.2 Policy and Priorities

The case for applied research in these areas is obvious from the above discussion. We have considerable strengths in the following areas at present:

* fermentation,
* animal viruses,
* plant viruses,
* plant pathology (fungal plant pathogens),

* plant genetic engineering,
* genetics and molecular biology,
* mycobacteriology (including TB),

with further strengths on the medical side that will not be commented on here. We should support all these areas where the expertise already exists, as they are all based on SA needs (they all arose from much needed applications, though many include very basic research), and are of proven quality.

The important point is not whether research is pure or applied but rather if it is good research. However 'pure' projects can be concentrated in areas which could ultimately lead to applied work. For example work on the nitrogen metabolism of the anaero- bic bacterium *Clostridium acetobutylicum* is based on the knowledge that this bacterium has in the past, and could in the future (depending on the price of molasses), be used to produce acetone and butanol, and the efficiency will depend *inter alia* on nitrogen metabolism. Similarly work on cellulases produced by rumen bacteria could be applied to developing a 'super-bug' capable of degrading more of the fodder supplied to cows and sheep, so making their digestion more efficient. Other projects, such as the development of virus and insect resistant plants, are more immediately applicable. However even they require some fundamental research into resistance mechanisms.

Thus we dare not neglect research into areas that might never have applications, even though we can try to choose projects in which results could possibly have practical implications. In particular concern has been expressed by our medical colleagues that basic biochemical and biophysical research as applied to the practice of medicine should be undertaken. However we should maintain some research in the very basic areas of understanding, because advances here have the potential to generate the biggest practical impact in the long term. Specific areas of concern are as follows.

14.2.1 Plant Molecular Biology

We need to stimulate plant molecular biology in this country, which has important applications, as discussed above, but is presently underdeveloped.

14.2.2 Biophysics

While biophysics is used as a tool by many groups, the subject itself is sadly neglected in SA, except perhaps for some departments of medical physics or biomedical engineering.

14.2.3 Cooperation with Africa

The subjects discussed above, particularly in the agricultural area, could form a fruitful basis of cooperation with the rest of Africa. For example, in a recent article on biotechnology and natural resources management, Okonkwo (1992) noted the following as areas that needed development in Africa:

* Plant biotechnology (clonal propagation, meristem culture, embryo rescue, pollen cultures, germplasm conservation, genetic engineering for herbicide and insect resistance);
* Microbial biotechnology (biofertilisers, industrial enzymes, single cell protein production, bio-insecticides, bioenergy through biogas production);
* Animal biotechnology (improved animal health, improved animal reproduction);
* Aquatic biotechnology;
* Health (development of rapid diagnostic techniques, vaccine production, development of therapeutic agents from local plant sources).

It would appear that we could play a major role in helping get such programmes going in Africa south of the Sahara.

14.2.4 Education

It can be claimed that biochemistry has a 'tap-root' nature for the life-sciences, equivalent to that of mathematics in the physical sciences, in that all the life sciences when studied at a fundamental level use the common language of biochemistry and molecular biology, There is thus a need to emphasize broad, exciting and attractive undergraduate programmes in biochemistry, the need for co-majors, and the importance of biochemical methodologies.

Doctors, nurses, medical and agricultural technologists, farmers and industrialists need to be aware of and understand modern developments in these areas so that they can exploit them for the benefit of all. Therefore a vital aspect of any future SA biotechnology programme is education to understand what is meant by and how to exploit biotechnology. One of the greatest dangers inhibiting the beneficial exploitation of biotechnology is rejection by lay people due to unwarranted fears or malicious dogma.

Furthermore, molecular biology/biotechnology are essential tools in all fields of biology and medicine. Human geneticists need them for detecting and ultimately protecting against genetic disorders. Medical microbiologists need them to detect and ultimately cure viral (e.g. HIV) and bacterial (e.g. TB) infections. Chemical pathologists and medical biochemists need them to dissect, understand, and control diseases and other disorders. Zoologists and botanists need them to unravel taxonomic relationships, identify genes and understand the physiology of organisms. SA needs such trained scientists. It is therefore essential to identify centres where excellent training occurs and support them. Labs should train scientists and then encourage them to move on and spread their expertise.

There is a good opportunity to use our expertise in this field to provide a base for collaborative work in Southern Africa, e.g. training workers from elsewhere in the sub-continent.

14.2.5 Ethical Committee

We have not discussed the ethical issues arising in this area, nevertheless, as in the case of animal experiments, this is an important and emotive issue. Again a special inter-disciplinary committee should be set up to consider these issues and make decisions on them, on the basis of public debate and negotiation. The MRC has just issued a set of *Guidelines on Ethics for Medicine Research*, which cover many of the points discussed.

14.3 Equipment

As in botany and zoology, there is a need for the basic equipment and materials used in molecular biology. These can be held at central resource centres in convenient places, accessible to the various active groups. However there is a limit to what can be done here. For example, it is sometimes necessary to utilise X-ray crystallography of proteins. At present we send them overseas for this analysis. It may not be practicable to introduce the necessary equipment in SA in the near future.

There is other specialised equipment that can and should be obtained, for example a gun for putting DNA into plants, which can be bought from the USA for R150,000. This is the kind of specialist equipment that should be available locally.

Chapter 15

Archaeology & Palaeo-anthropology

Archaeology: studies the remains of past human societies, ranging from pollen grains and rock art to skeletons and buildings, and uses this evidence to interpret the nature and functioning of those societies, and to understand the natural environments in which they lived.

This study is central to understanding the evolution of humanity and of society. The methods used in modern archaeology are similar to those of geology and palaeontology, for example, involving the understanding of stratigraphic relationships, the dating of materials to determine absolute age and isotope, constituent and other analysis of bones or stones to establish subsistence, trade or other social details. Palaeo-anthropology deals specifically with fossil human remains, and so is a special case of palaeontology. It extends the study back to the very origins of humanity.

15.1 Archaeology in SA

South Africa has a very strong tradition both in archaeology and in palaeo-anthropology (Tobias 1977), particularly through the work of Raymond Dart, who established the claim of Taung, near Kimberley, as a new genus of hominid, Australopithecus.

15.1.1 Origins

Southern African scientists, prominent among them Dart, Broom, Tobias and Brain, have played a significant role in the unraveling of the complex story of hominid and subsequent human origins. This is partly because the cavern systems of the Transvaal dolomite have preserved hominid remains along with associated faunal and stone artefact assemblages. It is important to note that only the northern parts of South Africa and parts of the East African Rift Valley have produced Plio-Pleistocene hominids. Many more Australopithecine fossils have come from the Transvaal sites than from all of the East African sites combined.

SA thus has the capacity to continue to contribute to the field both by generating larger samples of hominids and other fossils through excavation, and also by fostering the development of new kinds of analysis of the finds. Most recently, the identification of burnt bones and polished bone artefacts are examples of this, as are innovative attempts to reconstruct the diets of Australopithecus and Homo habilis from the analysis at UCT of trace elements and stable carbon isotopes in hominid fossil bone. The Transvaal Museum, the Department of Anatomy at Wits, and other Institutions house and curate the valuable fossils that already have been discovered, and thus attract many visiting scientists annually. In SA there is thus the combination of excavated and curated material, conservation experience, a wealth of depositional environment, and the range of analytical skills to make a substantial contribution to an internationally significant research agenda.

15.1.2 Modern Human Origins

SA has the sites and the research experience to contribute to the currently high-priority study of the origins of behaviourally and anatomically modern people. Large, well-preserved and properly curated assemblages of systematically excavated artefacts, together with features and bones of terrestrial and marine animals and marine molluscs, provide an established information base. Key collections are housed at South African museums in Cape Town, Kimberley, and elsewhere. These are evidence of long term interactions between people and landscapes, and are suited to studies that aim to unravel the complexities of accumulations brought about by carnivores, human and natural agencies.

Questions about early human behaviour, such as whether people were hunting or scavenging large carcasses, and when people began to make systematic use of marine resources, can also be addressed. The evidence can already be read to suggest that the earliest modern human remains, the earliest burials and grave goods, and the earliest shellfish gathering are found at South African sites. In addition, large assemblages of bones from carnivore lairs provide controls for interpretations of faunal remains thought to have resulted from human activity, as well as offering long term palaeoenvironmental and palaeoclimatic insights. Particularly dense concentrations of micromammals, often interstratified with archaeological levels, are very sensitive to past vegetation shifts. South African scientists have an enviable opportunity to contribute observations and to influence interpretations of the origins of our species.

15.1.3 Pre-colonial History

For most of human history people have been hunter gatherers, collecting wild plant and animal foods from their surroundings. Few hunting and gathering communities survived into the twentieth century, but of those that did perhaps the best known and described are the Kalahari San or Bushmen. Many key anthropological models of hunting and gathering derive from these studies of the San, and the extent to which the models may, or may not be, more generally applicable is currently the subject of heated debate world-wide. Southern African Stone Age archaeology is the history of San people, and as such is of interest to anthropologists and human scientists everywhere.

Southern Africa, like other continents colonised by European societies in the last few centuries, preserves a history that has to be retrieved by archaeological excavations. In the mostly arid subcontinent bones, plant remains and organic artefacts have survived to allow sophisticated analyses of diet, settlement patterns, and social organisation. Long sequences in rock shelters and caves offer the potential to extend back observations well into the Pleistocene. Combined with a rich and well documented ethnography and an associated abundance of painted and engraved images, the record is as good and as resolved as anywhere in Africa.

Already South African archaeologists have begun to contribute to such international debates as the social relations between hunters, herders and agriculturalists, the seasonal use of landscapes and resources, and gender as a feature of social and ritual behaviour. Isotopic and trace element analyses of human skeletons and food residues by South African archaeometrists have pioneered the questioning of previous assumptions and have shown the complexity of human use of resources. More innovative approaches are already being formulated to date rock art, to establish the source areas of ostrich eggshell beads, to reconstruct sea level histories, and to develop ways of recognising pre-colonial identities. Because the history of South Africa is largely to be derived from the material rather than the written record, archaeology has the potential to give back a history to South Africa's disadvantaged people. Large collections, considerable experience, and a vast archive of largely untapped buried evidence already exist.

15.1.4 Rock Art

Southern Africa houses one of the largest assemblages of rock paintings and engravings in the world. From radiocarbon dates on associated charcoals, the earliest painted slabs from southern Namibia are thought to be some 25000 years old, as old as any anywhere else in the world. At the other end of the trajectory, the work of Wilhelm Bleek, Lucy Lloyd and others on the 19 century southern San or Bushmen, the makers of the art, has left us with an invaluable corpus of information.

Study of this ethnography and art by David Lewis-Williams at WITS led to advances in interpretation that are of international importance. He has shown the ritual and metaphorical character of the images, and believes this insight will apply as well to other images of the late Pleistocene, such as those of the Palaeolithic in France. Stimulated by the wealth of imagery in SA, other perspectives have and continue to emerge. Only a fraction of the art has however been located and recorded, let alone studied in any detail, and the ethnography promises further insights. Furthermore, the wealth of paintings and engravings is matched by associated archaeological materials, and integration of the painted and excavated archaeological records remains an exciting and viable challenge. SA has the potential, both human and material, to remain at the forefront of research on the production of art by hunter gatherer people in late prehistory, and to contribute to new advances in related issues such as the dating of the art.

15.1.5 Palaeoenvironments

At a time of widespread concern about human impact on the environment and resultant climatic change, scientists are increasingly looking to past climates and environments to help refine models of global circulation systems. Archaeological sites contain valuable evidence of past temperatures, rainfall regimes, and floral and faunal communities. SA sites are of particular interest because of their long timespan, and because of the relative paucity of information from the southern hemisphere. Indeed, intensive study of southern hemisphere palaeoclimates and environments has been identified as a priority by the International Geosphere Biosphere Programme.

SA scientists have made, and continue to make, an important contribution in this area. Key facilities include the Quaternary Dating Research Unit at the CSIR, which provides radiocarbon (and other) dates, and is an internationally esteemed laboratory. Scientists from the University of Cape Town and the CSIR pioneered techniques of light stable isotope analysis which have subsequently become standard tools world-wide, not only in archaeology, but in botany, zoology, ecology and related disciplines. Facilities for such analyses exist in several institutions in SA, and the combination of technical expertise and an abundance of important issues to tackle are a real strength of the local scientific community.

15.1.6 State Formation

One of the most intriguing research questions in the pre-colonial history of Southern Africa is that of the rise of the Zimbabwe state and its relations with Indian Ocean traders. The move toward a more centralised political structure is visible in the large Iron Age towns of Botswana and South Africa at about 1000 to 1100 AD. Southern African archaeologists have accumulated large excavated collections from many of these sites, and have earmarked many more for future work. There is here the opportunity to research the connections between state formation, Indian Ocean trade, and the growth of indigenous technologies, such as architecture, iron smelting, and ceramics. This amounts to the archaeological reconstruction of the pre-colonial history of the bulk of the current South African population.

15.1.7 Historical & Maritime Archaeology

Because of its geographic position, halfway between Europe and Asia, southern Africa has been a meeting place for many different communities from three continents. This is witnessed by the great number of historical shipwrecks along the coast, which originate from at least 30 different countries, but also by the multitude of sites to be found on land. Shipwrecks, slave lodges, farm houses, military posts, wells, factory buildings, mines or harbour works - situated in the ground or underwater - all provide information on the interplay between different communities.

In addition, extensive use is also made of archival documents, iconography, vernacular architecture and other sources to complement the excavated material. This variety of both material and written sources is reflected in the many different collections lodged at various universities, museums, art galleries and archives in southern Africa and overseas. To deal with the documentation, analysis and conservation of excavated materials, laboratories have been established at most excavating institutions. Specialised laboratory facilities involving the use of X-ray, mass spectrometry and infrared spectroscopy are only available at major research centres such as the University of the Witwatersrand and the University of Cape Town, where also the only facility to deal with basic conservation of waterlogged materials is currently being established. South African Historical and Maritime Archaeology has thus the resources, both personnel and archival, to contribute to the growing field of the archaeology of colonial expansion and its effects on indigenous people.

15.2 The Case for Archaeology Research

Archaeology plays an important part in the study of the history of humanity and the development of civilisations. This is one of the foundations on which our view of ourselves, and so our world-view, is based. In particular palaeo-anthropology establishes the place of humankind in terms of Darwin's evolutionary theory - one of the most important insights into the origins of humanity to have ever emerged.

As has been explained above, SA is in a strong position to make a unique contribution to these studies because we have a very good set of archaeological and paleaontological evidence to hand, and the expertise to analyse this in an innovative way.

As SA changes, its history is being reviewed. Old explanations and evaluations of the past are being swept away. Old stereotypes of indigenous people and indeed of the whole sweep of African history are being challenged as a new history is constructed. This partly shapes the new order that emerges.

15.3 Policy and Priorities

The present research groups are innovative and strongly based. Policy should be to continue support of this work as at present, allowing continuation of the same lines of research. There could be an extension into the use of molecular biology in establishing evolutionary lines; the basis of expertise required for such a development already exists in the country.

There is already a degree of amateur involvement in archaeological research. As in the cases of botany and zoology, this is a trend that should be encouraged and supported. The other development that could be encouraged is greater cooperation with scientists from other parts of Africa in these researches. From the larger viewpoint, it is the issue of the role of Africa as a whole in the evolution of humanity that is of interest.

15.4 Equipment

Equipment required is similar to that for geology and palaeontology - in particular a range of microscope facilities, surveying and mapping equipment, X-ray and mass spectrometers and infrared spectrometers. These can be shared with other research groups. Physical imaging techniques (for example, use of ultrasound) has the potential to make some of the work much easier.

D: Earth Sciences

The Earth Sciences study the behaviour, distribution, and history on and in the Earth of the four basic elements of Nature: earth (Geology, Geomorphology), air (Atmospheric studies), fire (literally: volcanoes, but in modern terms: energy flows in the Earth's interior, oceans, and atmosphere), and water (Oceanography, Hydrology).

We consider in turn, 12: Geological Sciences; 13: Hydrology; and 14: Oceanographic and Atmospheric Sciences. While these studies are based on physics and chemistry, they also to some extent involve biology. They are important components of ecology, environmental sciences, civil engineering, economic geography, and urban and regional planning.

Chapter 16

Geological Sciences

Geology : the scientific study of the structure and evolutionary history of the Earth's interior and its surface (in particular, mapping and classifying landforms and rocks, and explaining their formation, composition, and spatial pattern). These studies, together with similar studies of other bodies of the Solar System, provide evidence relating to the Earth's origin.

Two important sub-disciplines are *Geochemistry*: study of the distribution and evolution of the chemical elements in the Earth's interior, crust, and atmosphere, and *Geophysics*: application of the theories and techniques of physics to the Earth's surface and interior. Specialisation within the general field of geology has established the following subjects as distinct fields of research and application: structural geology, igneous petrology, volcanology, metamorphic petrology, sedimentology, mineralogy, tectonics, crystallography, and stratigraphy.

The economic importance of geological studies relates to the discovery and exploitation of ore deposits, fossil fuels, construction materials, and underground water. Together with the related subject of *soil science*, many of the subdisciplines are important in civil engineering and agriculture. This subject and *environmental geology* are discussed in later sections.

The methods and concerns of geology overlap to some extent with those of palaeontology, because they are both involved with rock studies and evolution, and with oceanography (because of plate tectonics). Indeed it is important to use information derived from sedimentary geology and palaeontology to check and reinforce each other, e.g. in dating of rocks and in pursuing paleaoclimatology (the study of ancient climates).

16.1 The Present Position

SA has a strong tradition in some sections of the geological sciences, but is not as strong in others.

16.1.1 Geophysics

The Bernard Price Institute made a name for itself in 1937 through studies of the physics of lightning, and use of deep level mining to probe the detailed structure of the Earth's crust and mantle. In 1952, it introduced isotope geoscience to Africa: mass spectrometers were built and the ages of rocks measured from their radioactivity. Later work studied palaeomagnetism and seismology (the study of the frequency and distribution of local earthquakes).

Modern geophysics is largely concerned with (a) *Geodesy*: the study of the shape and gravitational field of the Earth, (b) the study of the Earth's interior through *seismology* (by analysis of reflection and diffraction of seismic waves), and (c) *Tectonics*: the study of rock movements and deformation, including particularly plate tectonics (the study of continental drift and growth of continents) and mountain building. New methods of analysis are available today through very precise satellite-based position measurements.

For various reasons, geophysical studies outside of mining houses are currently on the decline in SA. Indeed the formerly vibrant geophysics department at Wits has all but collapsed since its proposed relocation into the geology department; and consequently quality geophysics training at university level in this country is in serious jeopardy.

16.1.2 Geology and Geomorphology

Geomorphology studies landforms and processes at the surface of the Earth (in particular, the effect of volcanoes, sedimentation, ice ages, and weathering). Geological studies include (a) *Petrology*: study of rocks, determining their composition and how they formed, perhaps involving petrological experiments (trying to reproduce these processes in the laboratory); (b) *Sedimentology*: study of the sedimentary processes that led to rock formation, (c) *Vulcanology*: study of volcanoes, their eruptive products, and associated volcanic hazards; (d) *Economic geology*: study of ores and ore-forming processes; (e) *structural geology*: study of the deformation of rocks; (f) *Mineralogy and Crystallography*, study of the composition, structure, and habit of natural minerals, many of which are of economic importance; and (g) *Geochronology*: dating of rocks and fossils through a variety of techniques based on physics, chemistry, and biology. A major geological component is (h) *Stratigraphy*: correlating rock sequences from over the world.

Various groups in SA are actively involved in all these fields. These topics are affected by, and help investigate, the long term evolution of conditions in the atmosphere and in particular changes in its chemical composition; these are studied in paleaoclimatology.

16.1.3 Geochemistry

Traditionally, geochemistry is the study of the abundance and distribution of the elements and their isotopes, mainly on the surface of the Earth and in the mantle, but also in the seas and atmosphere. The wider context concerns studies of the distribution of the elements in the solar system (e.g. on the Moon and meteorites).

Strong groups have been involved in geochemical research in SA, with the emphasis of the research being both fundamental and applied. Applied studies are aimed at understanding the origin of many economically important minerals. Some examples:

(a) The primary occurrence of diamonds is in kimberlites, a volcanic rock which transported diamonds formed at depth to the Earth's surface. Yet not all kimberlites contain diamonds. Much research has been carried out to predict whether newly found kimberlites are likely to carry diamonds. This is being done by studies on the chemical composition of minerals such as garnet, ilmenite and chromite.

(b) After gold, coal is SA's biggest earner of foreign exchange. Projects are under way to determine the major and trace element composition of SA coals, and details of distribution of these elements within different coal seams. This should result in better and more effective mining practices, thus increasing the quality of the product and so resulting in less pollution of the environment, greater coal exports, and better prices for exported coal.

(c) A number of researchers are studying the geochemical evolution of the Bushveld igneous complex, one of the world's largest repositories of chrome and the platinum group metals. These studies are aimed at facilitating the discovery of new deposits within this immense intrusion.

The analytical techniques of X-ray fluorescence spectroscopy, mass spectrometry, ion chromatography, and electron microprobe analysis are being applied as tools in mineral exploration.

16.1.4 Marine Geoscience

Geology interfaces with oceanography in studying the interactions between rocks and sea and with processes forming the sea floor (Rogers in FRD 1990). We have strong work in this area too, aiming to understand long-term (thousand to tens of thousands of years) alterations in climate and oceanographic conditions from studies of the sediment record of the sea floor. Such studies both locally and in comparable areas overseas place historical fluctuations in weather - fundamental to farming - in their long-term perspective, and so help in management planning (see the section on climatology).

More immediately, geological studies of the ocean floor help in the search for off-shore gas and oil (Gerrard in FRD 1990) and in the discovery and exploitation of sea floor materials: phosphates, potash, diamonds, rare metals, building materials, diatomaceous earth, etc. (Bremner in FRD 1990). Finally sedimentological studies of the nearshore area help in planning coastal engineering works, while similar work in the deep sea helps in planning routes for sea-bed structures (cables, pipelines).

16.1.5 Mining and Engineering Geology

Geology gives information on location of faults and deformation planes, which is fundamental in construction of major structures such as bridges and dams. Thus this is an important input to civil engineering. The other major contribution of geology is in exploration - the search for minerals and underground water. These disciplines are well-developed in this country, indeed we have a strong tradition in exploration and mining geology.

Research continues to play an important role in improving these techniques, particularly as new methods, based on the one hand on aerial and satellite imaging, and on the other on exploration seismology, are introduced. This research uses as its basis the findings of the other branches of geology. it involves methods of 3-dimensional modeling and representation of the sub-surface geological structures using new computer graphics technology are being applied towards increasing the effectiveness of the geologist in mineral exploration. This can contribute to the enhancement of the economy, and to the safety of mining (e.g. design against sudden rock bursts)

16.2 The Case for Geological Research

Firstly, the case for research into Economic Geology (and associated exploration, mining, and engineering applications) is obviously strong. We have amongst the largest platinum, gold, antimony, vanadium, chrome, and diamond deposits in the world, as well as large deposits of iron, other base metals, and coal. These make a major input into the economy; exploration and extraction techniques need to be as highly developed - and suited to local conditions - as possible. The engineering applications just discussed are also important, and also need to be fashioned to suit local conditions.

Secondly, geological research is central to environmental studies as it plays a major role in studies of the various major and trace element cycles on the earth (e.g. carbon, nitrogen, oxygen, water) and their roles in ecosystems. It is particularly important in its contribution to understanding the movement and distribution of water, and the formation of soils. It is also central to evaluating the environmental impact of various proposals, through understanding erosional and coastal processes.

Thirdly, geology plays a major role in understanding the history of the Earth. We are well placed to participate in these studies, because we have a unique geological heritage in this country, providing valuable evidence of the history of the Earth. In particular, we have good exposure of ancient rocks that were formed very early in the Earth's history. Additionally, we have the expertise in dating methods needed to take advantage of this situation. Thus we are for example in a good position to take part in programmes to understand global stratigraphy (global correlations of rock layers of different ages), and in the task of continental reconstruction, in particular developing the details of the history of Gondwana, and the cyclicity of super-continent formation.

This 'theoretical' work is worth doing for its own sake; as in other subjects discussed above, we are in a position to make a unique contribution to world knowledge, and should take advantage of that opportunity (provided the cost is not too great). It is also important that the applied work and more theoretical studies are strongly interrelated, the theoretical providing the frame-work of understanding for the practical. Indeed new theoretical interpretations are often the key to making sense of what was before just a jumble of facts. This is true both in terms of theories of mineral deposition and in studies of climate and weather patterns in prehistoric times (this theme is developed further in the next section).

Finally, we are well placed for geoscience education - because we are faced with a hot-bed of problems to solve, and with plenty of readily available research material to use in the enterprise. Research is the keystone to that education.

16.3 Future Research Needs

World wide, the nature of geological research is changing. New trends in the geosciences have been evolving at a fast pace in the developed world; many of them forced by socio-economic needs and demands, viz. global change related studies, climate work, environmental and urban geology, water resources, hazard prevention, waste disposal management, engineering geology, minerals rights studies, geology and health, geo-resource economics, and so on.

In SA, geological teaching and research has traditionally been seen as providing specialists for the minerals industry which was a cornerstone of the economy. However the mining industry has been going through hard times, and the FRD no longer considers geological sciences as a priority area (in contrast to the solid support given under the old SANCOR and CSIR national programmes). Similar changes have happened in the USA, where the traditional areas (mining and petroleum) have largely fallen away.

More or less coincidentally with these developments there has been a spectacular growth of world-wide interest in things environmental. To some extent this has been a bandwagon, but there is a solid core of serious, scholarly endeavour to these activities.

By definition, the processes and factors to be investigated in such work are modern, but in establishing comparative data sets, and comparing with 'known' examples, long-term time series are often needed. It is here that Earth scientists have the edge. They are used to dealing with processes that have evolved through time, as well as having expertise in analysing certain physical and chemical data (sedimentary properties, fluids, etc.). In the course of environmental investigations even quite remote geological events can be relevant (for example, biological colonisations and extinctions, change in climate, geography and atmospheric/oceanic circulation and chemistry). The logic is that if we know what happened naturally in the past, steps can be taken to cope with future events. While the practicality of the logic is open to debate, the theory is not. Three examples:

- the speed with which deglaciation (or glaciation)occurs is not known. Are there sudden 'bursts' as thresholds are crossed, and how are these linked to climatic deterioration?

- What are the climatic,oceanic and biological consequences of CO2 and methane increases in the atmosphere?

- What are the rates at which species became extinct in the geological past? Are there useful geological analogues of scale to modern anthropogenic species destructions?

Skirting the question of what humanity could do to cope with or accommodate these catastrophes, there can be no doubt that an understanding of the dynamics will be infinitely preferable to not knowing the natural patterns. This would be true if only because such understanding is likely to have beneficial uses in hitherto unforeseen ways. Clearly this is an area where Earth scientists can be influential, and overseas there has been a swing towards both teaching and research in these areas, often with interdisciplinary programmes.

Many of the processes that need to be understood during research into environmental problems leave a readable signal in the geological record, mostly locked in sedimentary rocks. Here we can locate long time-series of data encoded in mineral composition, fossils, sedimentary structure, sedimentary geochemistry (both inorganic and organic, natural and man-made). Meteorological and other written records never go back more than a few hundred years, and usually only a few decades. These are too short to eliminate background noise. Geological records can be read to a resolution ranging from annual to millennia (depending on the nature of the rocks and the analytical method), and range in age from the youngest, modern sediments to strata many millions of years old.

Consequently Earth science contributions to most of the major environmental programmes (e.g. climate change, sea-level fluctuations, toxic waste disposal, soil erosion, coastal/ estuarine/wetlands management) entails an integrated approach to avenues of research in sedimentology, sedimentary geochemistry and stratigraphy. In addition because of the nature of the sedimentological record, the most complete time-series lie in marine rocks (in contrast to the destructive or at best intermittently accumulative nature of continental sediments: lakes are an obvious exception), so that the disciplines of marine geology and geophysics become extremely important. At present this work has low priority in research in South Africa, but there is a great potential for teaching and research in these 'soft rock' areas. There is also a crucial role to be played by isotope oriented work in geochemistry; this is strong at present.

Many of the exciting areas of research overseas relate to applications of integrated environmental approach in world-wide phenomena through a study of the world ocean system: climate change, palaeo-oceanography, upwelling systems, etc. via the international Ocean Drilling Programme. South Africa cannot afford to join the ODP as a full member, but if the spin-off experienced in other countries is anything to go by, some formal association would be very beneficial in stimulating marine sedimentological research.

A further area which needs developing is hydrogeology. This has obvious links with environmentally driven Earth science programmes and should not be neglected (cf. the following section).

16.4 Policy and Priorities

In view of the above comments, one can suggest that:

(a) research should be continued with the same analytic rigour but at a slightly reduced level in the traditional applications in 'hard rock', and economic geology areas, where there is considerable strength at present but a degree of oversupply of graduates;

(b) the 'soft rocks' areas with an environmental emphasis, and a substantial coastal marine component, should be the subject of increased research and teaching programmes;

(c) deep water marine research should be encouraged also, but this is expensive because of the ships and deep-sea drilling equipment required, so this should be developed in a collaborative way as part of international programmes (for otherwise we cannot afford it);

(d) we should increase our commitment to geohydrology, and to soil studies (geochemistry of the soil, weathering processes);

(e) there should be an upgrading of geophysical research and teaching, which is presently weak, for this is one of the foundations for the many of the other areas;

(f) in particular, we should keep up to date with, and if possible develop, modern remote sensing and analytic techniques. This requires ensuring that we have researchers adequately trained in these techniques (for example, accurate single-grain U/Pb dating).

16.4.1 Rationalisation of Education and Research

A thoughtful paper by Maarten de Wit (1993) explores the way that the present pattern of university research and teaching in SA could be rationalised to a more productive form. The essence of his suggestion is the realisation that SA universities have a natural geographic grouping - PWV area, Natal, Eastern Province, Western Province - each area of which contains two or more Geology Departments. Different expertise should be developed in these different centres, with sharing of resources between associated university departments, and with the specific intention to avoid unnecessary duplication and associated competition for funds between these centres. Some natural subdivision might include: solid Earth geophysics; economic geology; geochemistry; marine geology; coastal processes; and so on. The latter would also forge close links with departments such as oceanography, marine zoology, marine and coastal engineering, etc.

Such strategic rationalisation of geology departments would need careful planning (de Wit 1993). However the point is that such rationalisation could serve as a way of moving towards greater efficiency and ultimately viability of our geological research programmes; and also of moving towards greater equity by not unduly concentrating any new capacities at already strong institutions. It would also allow including those disciplines that are fragmented, frequently being relegated to the fringe of many departments. For example the plan could aim to also rationalise palaeontology, at present thinly spread over the country.

16.5 Equipment and Running Costs

Geology needs field observations (in the case of marine geology, this implies use of boats); remote sensing (aerial, magnetic, gravity, satellite imaging, seismic); and analytical tools.

Funding of field trips is a world-wide problem, but is essential for the training of students. Adequate provision must be made for these trips.

Whereas we have generally good analytical equipment for routine geochemical research, there are shortcomings in the more sophisticated geochemical and geophysical equipment available in SA. Some of the more important needs include an argon continuous-lasing facility; palaeo-magnetic laboratory; fission track dating centre; ion probe; thermal luminescence facility; ICP mass spectrometer; and seismic reflection profiling consortium. Marine geophysics equipment is also lacking.

A serious research effort must be adequately equipped. The need is for a strategic plan, to operate in conjunction with a rationalisation of activities as suggested above, to build up the needed equipment (and technicians who are adequately trained in their operation) over say a five-year period, where possible in cooperation with other disciplines with the same needs.

We also need access to a high pressure experimental laboratory; back-stripping facility; research reactor for geoscience research; and secondary ion-mass spectrometer. They are probably too expensive to justify purchase (the latter two each cost about R10m). However it is possible to send researchers to use these facilities overseas; this is probably the more practicable option.

Finally we need access to modern remote sensing facilities, specifically through access to remote-sensing satellites (again, this can be shared with other interested research groups, particularly in the environmental sciences), and adequate computer facilities for processing and displaying the resultant data. These should form part of the overall strategic plan.

Chapter 17

Hydrology

Hydrology is the study of continental water in its normal form: its properties, distribution, and circulation (the water cycle). It is closely related to meteorology and geology. Because hydrology determines the availability of water for human use, it underlies the interdisciplinary subject of *water studies*, which is of fundamental importance to the welfare and development of SA (see section 22.2).

The main branches of hydrology are concerned with the study of water in the atmosphere (*Hydrometeorology*), on the surface of the earth (*Surface Hydrology*), and underground (*Geohydrology*). On a global scale, it relates to *Glaciology*, the study of natural ice (for example in glaciers, the ocean, and the Antarctic), but in the local SA context this is not an issue at the present time.

17.1 Current Position

Water resources - essentially rivers in SA - are strategic resources under severe and mounting threats, so that many once perennial systems are now flowing only seasonally. Thus, over-abstraction (taking out more water than can be maintained in the long term) is the primary abuse of the resource, driven by a burgeoning population growth. Consequent lack of potable supply infrastructure, township development under apartheid without appropriate supply and treatment, organic and acid rain pollution, salinisation (the result of over irrigation) and sedimentation, and over-abstraction form the major threats to continuing integrity of the ecosystems that supply the resource.

SA is in the fortunate position of having an extensive water research programme under way under the auspices of the Water Research Commission. This far-sighted project encompasses all aspects of hydrology (see for example Cousens *et al* 1988), as well as many issues arising under the wider ambit of water studies. University units carrying out water research include the Hydrological Research Unit at WITS, the Fresh Water Research Unit at UCT, and an agricultural hydrology group at Natal University (Pietermaritzburg); other groups are the Hydrological Research Institute (Department of Water Affairs) and the National Institute for Water Research (CSIR).

International collaboration, particularly with Australian scientists and with USA people, is already well established. For example, the FRU initiated such contacts in 1991 with an extensive series of visits and workshops; reciprocal visits occurred in 1993 and 1994.

Work is being carried out in the following areas:

17.1.1 Hydrometeorology

This research is a specific aspect of meteorology:

(a) To develop adequate understanding of spatial and temporal characteristics of precipitation and other potential atmospheric sources of water (dew, for example). This requires developing measuring techniques and systems, together with appropriate information systems, thereby establishing the spatial and temporal amounts and quality of atmospheric water and of precipitation, and sophisticated statistical analysis. Hydro-meteorological data are pretty good, thanks to the WRC.

(b) To characterise and understand weather and climatic impacts on water availability. This modeling programme requires measuring and modeling weather variables required for energy balance assessment; measuring and estimating evaporation and evapo- transpiration; studying and predicting the effect of climate change on supply and quality of water. The ultimate aim is on the one hand, to combine this work with weather-forecasting techniques in order to obtain estimates of water availability in the future; and on the other, to study and predict the effect of microclimate manipulation on the supply of water.

The WRC has spent ten years of extensive research on cloud seeding experiments, resulting in a considerable amount of knowledge of precipitation development processes peculiar to convective clouds in the Eastern escarpment and highveld regions of South Africa. This knowledge has led to the development of a cloud-seeding methodology, using hygroscopic nuclei, specifically designed to enhance the precipitation efficiency in such clouds. Randomised seeding experiments, supported by cloud physics investigations, suggest a considerable enhancement of precipitation between 20 and 50 minutes after seeding. It is contemplated to now extend this successful research from the seeding of individual clouds, to seeding for area-wide rainfall enhancement. There is international interest in this work.

17.1.2 Surface Hydrology

Research into surface hydrology concerns rivers, lakes, and dams. It investigates hydrological processes (precipitation, energy, evapotranspiration, soil processes, runoff producing mechanisms, channel processes) and their consequences for surface water and catchments. Particular issues of concern are determination of surface water resources (characterisation of volumes, flow, return flows) and their quality (salinity, sediments, pollution by industrial or municipal inflows, pollution from fertilisers or pesticides).

This work depends on good data, obtained both by remote sensing and by ground-based instrumentation, and on model development and testing. As well as determining the potential of conventional water sources, one of its aims is to investigate unconventional water resources (atmospheric moisture extraction, iceberg exploitation) and conservation possibilities (evaporation/transpiration suppression).

Climatic data are reasonably good, but although many SA rivers are gauged, we are often forced to make recommendations of instream flow requirements to maintain ecosystem functioning based on simulated flows rather than "real" data. Often gauges are incorrectly sighted, malfunction or are buried under sediments. In other words, surface hydrologies are more often than not guesses, and are inadequate to the current needs of planners, managers, conservationists and ecologists.

There has been extensive work in SA on forest hydrology. We were among the first countries in the world to set up catchment experiments (in the 1930's) and still have strong research capabilities in answering the important question of the effects of different land-use options on stream runoff. Our research effort (mostly in the CSIR and Forestek) is of international quality and widely respected.

17.1.3 Geohydrology

This is concerned with the location and quality of underground water, and determining the sustainable yield from aquifers. It is thus a branch of exploration geology, building on geological methods and expertise in order to develop methods of reliably locating and estimating hidden water resources. It also aims to determine potential and actual ground water contamination.

17.2 Policy and Priorities

This research is of very high developmental priority. While good research is being undertaken in all the subject areas mentioned, it is concentrated in somewhat isolated units. However the topic is so important that the scope of this research should be broadened, being fully integrated into studies in the broader area of Water Research (discussed below), and extended to all areas of SA. Thus a national plan for water research should ensure existence of strong regional centres of expertise in all the major regions in SA (certainly PWV, Natal/Kwazulu, Eastern Cape, OFS, Western Cape), with associated outstations of substantial capability (e.g. in the Northern Transvaal and all the 'homeland' areas).

These studies depend on good quality data. While on the one hand satellite images are very helpful in assessing the large-scale picture, on the other detailed local collection of data is essential as the basis of local policy choices. In particular better river flow measurements are essential.

Although there is an extensive water research programme (under WRC and DWAF) with some input from FRD, the ecological research is in its infancy and the researchers are under considerable stress to provide data for management of systems that have very few historical data.

As in the cases of botany and zoology, hydrology is an area where informal sector and school-based data collection could play a major role, both for its own sake, and because of the very important educational role this can play. Excellent work of this kind is already under way, for example through the Umgeni Water/Amanzi project (see e.g. *On Stream*, 1993). This work has many benefits:

(1) Making science accessible and interesting to school children. This is essential: the public perception of science as being Difficult and/or Dangerous is worrying. Everyone needs some basic understanding of what science

is, and also could do with a bit of healthy skepticism.

(2) It takes science out of the laboratory and into 'real life'.

(3) It allows community involvement and in fact provides data on which communities can base real decisions about their own health (clean water) and water resources.

(4) It can (with a great deal of caution) be used to collect useful data about systems that are poorly understood.

(5) It can provide the basis of environmental awareness, which is itself a critical issue. When so many people need houses, jobs, etc., it is very easy to lose sight of the fact that environmental issues are present all the time and that some of them cannot wait to be tackled at some future, more prosperous time.

Hydrology is an area that offers good prospects for international collaboration, and in particular research collaboration within Africa. Indeed many catchment areas, rivers, and irrigation projects cross international boundaries, so research work that crosses these boundaries is essential. SA can provide an Afrocentric view of development, management, and understanding of processes, which is different from the normal Eurocentric view.

17.3 Equipment and Personnel

At the high technology end, there is a need for access to remote sensing data, particularly from satellites, and associated GIS computer systems. On the low technology side, there is a need for cheap and easily usable equipment to estimate water volumes and kits to test water quality, such as the Catchment Action Starter Kit developed by R O'Donoghue at the Natal Parks Board.

There is also a need for local texts on the subject, as well as the development of locally applicable computer models of stream processes in relation to hydrology. We are dramatically short of fluvial geomorphologists to address the enormous problems of river regulation of flows by dams in this dryland environment of ours.

Chapter 18

Oceanographic & Atmospheric Sciences

Oceanography: the study of the physical, chemical, geological, and biological properties of, and processes in, the oceans. In this document, Marine Geoscience and Marine Biology are treated under the headings of Geology (section 16.1.4) and Ecology (section 19.4) respectively. It has been suggested these should all be regarded as part of a broader subject of Marine Sciences; but that should then be extended to the context of making management decisions, which is here regarded as part of environmental studies (see sections 20.7.2 and 20.7.3).

Thus Physical Oceanography and Marine Chemistry are the main branches of Oceanographic Sciences dealt with here. In understanding these topics, more is needed than a study only of the physics and chemistry of the ocean. The study of chemical oceanographic processes is not viable without appropriate biological, microbiological, and geoscience inputs. Thus oceanographers take into account the effects of marine organisms, especially insofar as they are important in influencing the chemical and optical properties of the oceans. Oceanography is important as the basis of understanding fisheries (important economically) and coastal processes (important sociologically and environmentally).

Because of air-sea interactions, oceanography must take into account the atmosphere; which in turn cannot meaningfully be studied without taking the ocean into account. Research into the physical and chemical properties of the atmosphere is formalised in *Meteorology*: the study of short term changes in weather based on processes in the earth's atmosphere, and *Climatology*: the study of longer term variation in weather (30 years and more). These in turn are essential elements in the broader study of Atmospheric Sciences. These inter-related subjects are important because of their role in understanding weather patterns, fundamental to food production and the environment. In particular they are the foundation of understanding global climate change, a topic of major concern to humanity at the present time.

18.1 The Present Research Situation

SA has a small but strong oceanography community, working in all the main areas of the subject (see pp. 63-69 in FRD 1990), although modeling of physical oceanographic processes has fallen badly behind in the past decade. This group has made a significant international impact; Prof Eric Simpson has been Chairman of the ICSU scientific Committee on Ocean Research, Prof Vere Shannon is Vice-President of IAPSO (the International Association of Physical Sciences of the Ocean), and Prof John Field is Chairman of the IGBP Joint Global Ocean Flux Study.

18.1.1 Physical Oceanography

This studies the distribution of physical properties of sea water such as its temperature, salinity, and density, and the forces causing motions of the water together with the resultant motions (Schumann in FRD 1990). The air-sea interface is important in exchanges of heat, moisture and momentum that are basic to the oceanic currents and the energy budget of the ocean (Walker in FRD 1990).

Open ocean circulation patterns such as the Agulhas and Benguela current systems (Grundlingh and Lutjeharms in FRD 1990) are important in determining local ocean conditions and climate patterns, while associated upwellings of sea water are important for fisheries (Shannon in FRD 1990). On a smaller scale studies of waves, tides, and current patterns are undertaken; these are important in understanding near-shore conditions.

18.1.2 Marine Chemistry

Ocean chemistry is affected strongly by biological processes, precipitation, river water influxes, and the air-sea interface (Lord in FRD 1990). It is central to understanding global element cycles fundamental to the biosphere, such as the carbon, nitrogen, and phosphorus cycles.

Marine geochemistry overlaps into marine geoscience and biology. Its sophisticated analysis techniques are fundamental to studies determining the effects of chemicals discharged into the sea from factories, cities, or by accident (Lord in FRD 1990). Unfortunately we now have almost no marine chemists left in SA; this is a serious gap.

18.1.3 Meteorology

Meteorology studies the weather (temperature, rainfall, humidity, and sunshine) and weather prediction, to develop weather forecasting tools for better resource management (Edwards and Walker in FRD 1990). This is the foundation of Hydrometeorology. Research studies ocean-atmosphere interactions in relation to weather and climate; energy budgets; precipitation mechanisms and stochastic modeling. It is concerned particularly with methods of prediction of extreme events (floods, droughts).

In 1958, Dr. A P Burger made a fundamental contribution to understanding weather modeling (Jackson 1977); some academic work on weather forecasting continues today. Routine weather forecasting is the concern of the Weather Bureau, using standard weather models imported from Europe. It is heavily dependent on good quality data collected from stations on the ground, from buoys and ships, from balloons, and by satellite.

18.1.4 Climatology

Climatology studies the same issues on a longer timescale, and is centrally concerned with global climate change. Here as well as geological processes, we cannot avoid considering the effect of the biosphere on the atmosphere, indeed it is believed that the present chemical composition of the atmosphere has to a large extent been determined by biological processes and that humanity is succeeding in inadvertently altering the natural cycling of climate change and thereby regional weather patterns.

SA is taking part in the IGBP international effort to understand global climatic change through the South African Global Change Programme (SA-IGBP). Many inter-related physico-chemical aspects are being studied, including ocean and atmosphere modeling, palaeoclimatology, climatic change and variability, the dynamic effects of marine weather systems affecting SA, and ozone variability over SA . These, combined with significant biological, hydrological, and agricultural studies combine into an impressive effort to attempt to predict possible impacts of global climatic change on the Southern African region (see e.g. Schulze and Kunz, 1993).

18.2 Organisation of Ocean & Atmospheric Sciences in SA

These fields are characterised by interdisciplinary and inter-institutional cooperation, both nationally and internationally. This must be maintained and fostered. They are accordingly not suited to being carried out in private research laboratories where competitive advantage is the motivating principle. At present a number of statutory bodies exist to foster and undertake research and monitoring in these fields, e.g. the Sea Fisheries Research Institute, the Weather Bureau, the Water Research Commission. These bodies work very successfully in close cooperation with a number of universities, with obvious benefits to both partners. This synergetic relationship should be maintained and fostered.

At the Universities, a number of interdisciplinary centres of excellence have emerged, e.g. the Centre for Marine Studies at UCT, the Climatology Research group at Wits, the Ozone Research group at the University of Natal. Each has its own field of specialisation and there is little duplication. This structure should be encouraged, with an overall strategic plane - taking 'market forces' into account - determining the location, field of specialisation, and size of centres of excellence.

Appropriate, scientifically based monitoring is of critical importance in oceanographic and meteorological research, and is probably the most threatened aspect of oceanography and meteorology at present. The crucial importance of long term monitoring needs to be recognised and adequate funding set aside for this specific purpose as soon as possible. Monitoring is not a function of a university based research organisation, and properly belongs in the realm of responsibility of the state organisations, but, as with all aspects of meteorology and oceanography, appropriate monitoring programmes are best designed through broad interdisciplinary and inter-institutional cooperation.

The use of satellite remote sensing is a cost-effective means of monitoring on the scales needed in oceanography and climatology. Technical expertise in this field needs to be built up in collaboration between the universities and statutory bodies.

18.3 The Case for Research

The oceans and the atmosphere are the global commons. They belong to all of us. The ocean is the storehouse of the sun's energy on the earth. The atmosphere is the conveyer of that energy to the land. The recent threat of global climate change has made humanity frighteningly aware of how dependent we are on oceanic and atmospheric processes, and aware of how much more we need to learn about these processes to protect our vulnerability.

Oceanography and meteorology are integrated fields of scientific endeavour which use the tools and skills developed in the fundamental disciplines of mathematics, physics and chemistry to understand the functioning of the natural physical environment. The processes in the oceans and atmosphere impact on, and to a lesser extent are affected by, biological and geological processes. The role of the ocean and the atmosphere in the hydrological cycle is of particular importance to agriculture and the development of societal structure (e.g. energy supply and water storage).

Oceanography and meteorology are particularly appropriate fields of research for SA, for a number of reasons.

(a) Better understanding of the local and global oceanic and meteorological processes has direct application to agricultural and infrastructural planning, and is especially important in Southern Africa which is a semi-arid country prone to periods of drought.

(b) SA scientists are excellently positioned geographically to be able to study three major oceans (Indian, South Atlantic and Southern) and important phenomena such as the Southern Oscillations, and thereby to contribute significantly to understanding their influence on both local weather and climate, and on global change.

(c) High quality research in these fields is built on a solid training in mathematics, physics, and chemistry. In turn oceanography and meteorology impact on zoology, botany, agriculture, energy supply, planning, and many other fields. They are thus truly interdisciplinary topics and as such are especially suited to a country such as SA as their study encourages the relatively small number of scientists to work together synergistically, thereby maximising their contribution.

(d) It has been shown that local studies in these fields have global implications and there is ample scope for international collaboration. Because of the paucity of scientists in the Southern Hemisphere, SA oceanographers and meteorologists are actively encouraged by the international scientific community to assist in filling the vast gap in information about Southern Hemisphere systems. This international collaboration will be essential for fostering and maintaining the standard of SA science in the future.

(e) Atmospheric research benefits from the fact that we are close to the ozone hole. Indeed the Physics programme at the Antractic base (SANAE) has a special role to play here, as this base is ideally situated for upper atmosphere research, in particular for investigating the ozone hole and the effects on the upper atmosphere due to the seasonal variation of the polar vortex. Satellites do not come far enough South to provide the needed observations, which are important to understanding processes in the upper atmospheric systems.

(f) Skills, expertise and infrastructure already exist in these fields in SA. These can be built on relatively easily to serve more of Africa which so desperately lacks infrastructure and is so dependent on climate.

(g) Oceanography and meteorology are sciences of the future in that they are totally consistent with the scientific philosophy of the 21st century whereby scientists will be called upon to assist mankind to live in sustainable harmony with nature.

(h) Studies in oceanography and meteorology can contribute effectively to both fundamental scientific understanding and improving quality of life, when practised at many different levels. For example, meaningful contributions can be made by the oceanographer with a Ph.D. in fluid dynamics, and by the meteorologist with a general geography background. This diversity makes these fields particularly suited to a country striving to bridge the gap between people with first world and third world trainings.

(i) Oceanography and meteorology are research fields which can be pursued at relatively low cost. Admittedly some of the infrastructure that is required is expensive (satellites, research vessels) but this very expense has resulted in inter-institutional and international collaboration and sharing of infrastructure being the norm. They are fields which have been characterised by sharing of facilities from which SA has benefited.

18.4 Policy and Priorities

The environmental problem ultimately of most importance to South Africa's economy and most aspects of its society is the likelihood of global warming and changes in rainfall. The livelihood of large numbers of rural people is closely tied to sufficient and timely rainfall, the agriculture of the subcontinent being at best marginal. Thus oceanography and meteorology are subjects of increasing importance because they study those oceanic and atmospheric systems that strongly influence SA climate and weather, and thus have major importance to the well-being of SA. They are fields in which we have considerable strength together with a history of international and local collaboration and interaction. They are thus research fields which should continue to be strongly supported in SA, as part of a broad programme of research in ocean and atmospheric sciences.

Research should be so funded that the three essential components of research in these disciplines will be healthy and innovative.

First, there should be a solid source of excellent teaching and basic research of international calibre in these subject areas as well as in the basic support subjects, such as the physics, mathematics, botany, zoology, and geology on which they depend. Mathematical modeling of physical oceanographic processes has fallen badly behind and needs to be strengthened urgently.

Second, there should be permanently established and well-endowed institutions of the nature of national laboratories that would undertake long-term research in those components of the atmosphere and the oceans that are recognised to be of national importance and that address national needs, such as environmental monitoring. Such institutions should have some formal connections to tertiary education in order to maintain their research quality and interest.

Cooperation and coordination between these three tiers of research institutions in the field of marine and atmospheric science should be continuously fostered. High quality proven research should be facilitated by adequate funding of research groups that have proven their excellence (with continuous monitoring of the success with which each R&D institution in the marine and atmospheric sciences meets its specific goals.)

This support should encourage national and international collaboration and an openness to the importance of understanding the global system, recognising science's responsibility to help protect the planet for future generations. This means in particular a concern for global climatic change, and its interaction with the biosphere. Three particular issues are worth mentioning.

18.4.1 National Organisation

The existing oceanographic and meteorological research organisational structure in SA (a limited number of key statutory bodies collaborating well with university centres of excellence) will serve these sciences well in the future. Insofar as change is needed, the organisations which produce work of the highest quality and find the most appropriate niche should be encouraged, in the framework of a plan that ensures overall research needs in the area are met.

18.4.2 National and International Cooperation

Science research policy in SA should aim to foster interdisciplinary research appropriate to the 'global village' of the future; Researchers should be encouraged to assume a global responsibility.

Thus another important element in stimulating research in these fields is active encouragement of participation in appropriate international and national scientific research fora. These range from international research programmes such as the International Geosphere Biosphere Programme (IGBP), the World Ocean Circulation Experiment (WOCE), the World Climate Research Programme (WCRP), and the Joint Global Ocean Flux Study (JGOFS), to regional and national research meetings such as the annual meeting of the SA Society of Atmospheric Scientists (SASAS) and the triennial National Oceanographic Symposia. The importance of exchange of ideas cannot be overrated.

18.4.3 Provision of Coordination Support

In a multi-disciplinary, multi-institutional field such as global climate research, the provision of adequate coordination support is imperative to producing applicable, state-of-the-art scientific results, and ensuring their integration with research efforts in other fields and other parts of the world.

18.4.4 Informal Sector Data Collection

As in other cases discussed above, meteorology is an area where informal sector and school-based data collection could play a solid role, for example through establishing a network of school weather observation stations. Given adequate checks on the data collected, this should be strongly encouraged.

An environmental research programme that could do useful science while drawing many participants at tertiary and possibly even secondary level both in this country and beyond our borders would be the establishment of a network of ground-based UV sensors for the study of ozone effects in SA and further north.

18.5 Equipment

Data collection for oceanography requires shore, offshore, deep sea, and satellite contributions. major marine research assets in South Africa are the three fisheries research ships (*Africana*, *Algoa* and *Sardinops*) and the antarctic research ship (*S. A. Agulhas*). These vessels are owned and managed by the Department of Environmental Affairs, and are highly specialised research facilities in their own right. Without these essential tools, South African Marine scientists would not be able to undertake much of the research, monitoring and assessment which is necessary for the wise management of the living marine resources and other uses of the marine environment. However such research vessels are expensive; their use should therefore as far as possible be undertaken as part of international collaborations, and more use should be made of relatively inexpensive satellite data.

South Africa should link in with international efforts such as the Global Ocean Observing System (GOOS) because we are so well positioned to be able to offer an excellent location to partner nations and we cannot afford high-technology systems on our own. Again in the computing and modeling areas, we should link in with international efforts, so that we may gain access to modern super-computers elsewhere, but this requires investment in modern work-stations to act as an interface to supercomputers and provide the basic equipment needed to encourage young modelers. Physical oceanography cannot progress without the tools to model our understanding of ocean dynamics.

E: Environmental Sciences

In this section, we discuss two subjects under the broad heading of Environmental Sciences, namely, 15:Ecology, 16: Environmental Studies.

It is here that the distinctions made at the beginning of part II of this document become important. In the way we use the terms here, *Ecology* focuses on interacting natural systems in themselves, and so is an integrated science. It gives limited information on management policies: that is, it discusses scientific (ecological) aspects of management, but without relating this in any detail to costs and social aspects. In contrast to this, *Environmental studies* leads on to full management and policy aspects, and so integrates information from ecology with subjects such as economics and law, and has political dimensions; thus it is an interdisciplinary science.

It is fundamental to recognise and make explicit the role played by these other disciplines in environmental studies, inherent in its nature because it is an applied discipline. Consequently it is also important to separate out those aspects - studied by botany, zoology, meteorology, environmental physics, chemistry, geology, and in particular the interactions characterised by ecology - that are independent of the economic, social, political, and ethical foundations chosen for policy and management decisions.

Chapter 19

Ecology

Ecology: that branch of biology that studies the interrelationships between organisms and with their environments, on the basis of field observations, systems analysis, simulation, and experimental work in the field.

Ecology is the foundation of understanding our natural environment, and the effect of our actions on it. Thus it underlies environmental studies and conservation biology, as well as sound farming practices. As it analyses the interactions between animals, plants, weather, water, and the soil, it is an integrated science with major components from zoology, botany, oceanography, meteorology, hydrology, and soil science, and with important contributions from environmental physics, chemistry, and geology.

While ecology is in principle a unitary subject, it is often regarded for teaching purposes as being comprised of population ecology, evolutionary ecology, community ecology, physiological ecology, systems ecology, and behavioural ecology. Physiological ecology involves environmental chemistry, geochemistry, physics, and geophysics. However the nature of an ecological system depends greatly on the kind of environment in which it is situated. Accordingly for research purposes it is more convenient to categorise ecological studies in terms of the kinds of environment considered, within the main classification of *terrestrial ecosystems*, *inland aquatic ecosystems*, *marine (coastal and oceanic) ecosystems*, and *estuaries*.

19.1 The Present Situation

There is presently great vigour in international ecology, formalised and coordinated through a major series of international programmes, meetings, and conventions labeled by a bewildering series of acronyms. These studies are driven by the new international concern for environmental affairs in general, and in particular the issues of long-term sustainability of natural systems and the effect on them of the ozone hole, global warming, and acid rain. However ecology is still very much at an empirical stage; *major* theories are yet to be developed at the ecosystem level.

There is a similar situation in SA, where much good quality ecological research is being carried out, often as part of one or other of the international programmes.

Indeed SA takes a leading part in some of these programmes, as exemplified by the fact that Prof J G Field of UCT is Chairman of JGOFS (Joint Global Ocean Flux Study), a core project coordinated by the international Scientific Committee on Ocean Research (SCOR), while Prof T Partridge of the Transvaal Museum is convener of PASH (Palaeo-climates of the Southern Hemisphere) which forms part of the core project PAGES (Past Global Changes). The umbrella programme for these activities is the International Geosphere-Biosphere programme (IGBP).

19.2 Terrestrial Ecosystems

The aim is to study the composition and interactions of the components of these ecosystems, and to characterise for example the energy flows and chemical cycles taking place. In doing so one has to consider all the elements of the natural environment: the physical landscape (geology, geomorphology, soils, climate), vegetation, zoogeography (see Fuggle and Rabie, Chapter 2, for a summary of these elements in the SA context). One wishes to understand the effect of weather changes, fires, floods, and interventions that we may make. The results may often be surprising, for instance discoveries of the major role played by insects and bacteria in some ecosystems, and the fact that fires play a positive role in ecosystem development (if not too frequent).

Following on the International Biological Programme of the 1970's, the CSIR launched the South African terrestrial biome projects under the auspices of the National Programme for Environmental Research. All of these projects enjoyed varying amounts of success. They ran for approximately ten years from the late 1970's. The projects were truncated shortly after the Foundation for Research Development assumed responsibility for them, but some work is still underway in the form of Forums designed to keep alive the same spirit of interdisciplinary research.

Why were the biome projects successful? There are six main reasons.

(i) They fostered a culture of cooperative, inter-disciplinary research.

(ii) They provided a platform for young scientists to compete for research funds.

(iii) They promoted interaction between scientists, managers, and the general public.

(iv) They had a democratic basis in that research policy and funding decisions were made by a steering committee for each project. The steering committee, however, was nominated by CSIR personnel.

(v) They promoted internationalized South African terrestrial ecology.

(vi) They had a focus on particular systems, were adequately funded, and were *long term.*

No other country had similar programmes, which were the envy of ecologists world-wide.

The biome projects were responsible for the 'golden era' of terrestrial ecology in SA. It is very important that future policy is informed by the successes (and failures) of this innovative and productive era. However one should note the following: The terrestrial biome programmes: fynbos, Karoo and savanna have been primarily run by plant ecologists with relatively little involvement of zoologists. The reverse is true of the Benguela Ecology Programme, which is primarily zoological and fisheries linked.

19.2.1 Savannah Biome Project

This project, started in the mid-1970's, was based at Nylsvlei, north of Pretoria. The project reflected the site-bound ecosystem bias of the IBP programmes. Much effect was put into quantifying ecosystem fluxes with less emphasis on population dynamics and natural history studies. However excellent work was done by Owen-Smith's group on herbivory.

Despite these limitations, the project was successful internationally at a time of deepening academic isolation. The project's achievements have recently been summarised in a book published by Cambridge University Press (Scholes and Walker, 1993). However it has not been well received by farmers and managers (who regard it as too academic).

19.2.2 Fynbos Biome Project

This project (CSP 1978) surveyed Fynbos ecosystems in detail. The topics covered may be judged from the contents of the preliminary synthesis (Day *et al* 1979): Climate; Geology, geomorphology, and soils; hydrology and hydrobiology; fire; palaeo-ecology; phyto-geography; zoogeography; plant ecology, animal ecology; invasive weeds; conservation; conclusion and recommendations (relating to conservation and management).

The Fynbos Biome Project differed fundamentally from the Savannah Biome Project in that it was not site bound; covered a broader base of approaches (ecosystem to population) and disciplines; involved a wider range of institutions; and interacted directly with managers and the general public.

The FBP was a spectacularly successful project resulting in significant advances in the understanding of fire ecology, maintenance of biodiversity, soil nutrient diversity, biogeography and palaeontology. The project aroused much interest internationally, and the major research results have recently been summarised in a book published by Oxford University Press (Cowling 1992). Work is continuing at a reduced level under a Fynbos Forum.

19.2.3 Grassland Biome Project

SA has an excellent history of research into the management of grasslands as a grazing resource. It is surprising therefore that the GBP did not build on this heritage. Rather, the project focused on the description, using formal phytosociological techniques, of South African grasslands. There was limited activity in modeling grassland dynamics.

19.2.4 Forest Biome Project

From the outset, the Forest Biome Project emphasized the growth, form, structure, and biogeography of South African forests; few experiments were performed in forests. Thus whilst no major financial venture, it did not move beyond an essentially descriptive and static level. Little progress was made in understanding the dynamics of forests, despite an excellent record of management for sustainable production in the Southern Cape.

The project failed to produce many international level publications or international interest. At a local level it failed to stimulate the formation of any special programmes at universities.

19.2.5 Karoo Biome Project

This project was initiated in 1987 and terminated in 1989. In developing this project an attempt was made to learn from the mistakes of the other projects. A study site was identified in the southern Karoo for long-term research (more than ten years) required to understand processes in arid lands. Despite truncation, the projects initiated under the KBP have made significant advances in our understanding of Southern African Arid lands. These have been translated into explicit guidelines for range management. The KBP had lively interaction between researchers, managers, and farmers.

19.2.6 Desertification

A series of projects are studying arid zone ecology, desert ecology, and desertification. The latter is a topic of considerable importance, and also the subject of controversy. What is clear is that Karoo productivity has dropped considerably this century. The causes, and possible remedies, need clarification.

19.2.7 Wildlife Studies

Various studies of wild life systems, particularly in the Kruger Park, have been carried out in depth as part of successful wildlife management programmes by the National Parks Board, in collaboration with university scientists.

19.3 Aquatic Ecosystems

We contrast these with marine ecosystems, dealt with below.

(a) The Inlands Waters Ecosystems Project (IWE) was part of the CSIR's "Cooperative National Scientific Programmes" (CNSP). It mostly funded work on man-made lakes (e.g. Hartebeestpoort, LeRoux, Midmar, Woeras) and on e.g. the Pongolapoort floodplain.

The Hartebeespoort project was remarkably successful in terms of its objective; some excellent work came out of it, largely on the dynamics of bacterial and phytoplankton in a very eutrophic system. However this is not necessarily very helpful in terms of management. The LeRoux and Midmar work was good but more limited. The Pongola Floodplain work was one of the first studies in which the sociological aspects of water management were seriously addressed in SA (see the final report: Heeg and Breen, 1982).

(b) CSIR also began a Wetlands Programme in the late 1980's, just before the CNSP folded; however little work was done.

(c) Major inland waters projects: Some excellent work has been done on rivers in the past, but little on ecological processes in them. At the moment however, with the exception of a small amount of 'fundamental' work on riverine ecology, almost all the work in this country is directed towards the production of guidelines and management tools for the maintenance of aquatic ecosystems in some semblance of 'naturalness'. This is partly because far more funding is available for directed research, and partly because aquatic biologists are aware that if they do not pause right now to assist in the conservation of aquatic ecosystems, there aren't going to be many worth studying in the near future.

(d) The Water Research Commission has established a Coordinating Committee for Water Ecosystem Research, which, in 1992, produced a master plan/guideline for research in aquatic ecosystems.

(e) The ongoing research programme directed at water requirements of the Kruger National Park, is a noteworthy collaborative and multidisciplinary research programme with co-sponsorship by the WRC, FRD, Department of Water Affairs and Forestry, Department of Environmental Affairs, and the National Parks Board. This coordinated research programme focuses on the conservation and functioning of the Park's aquatic ecosystems.

19.4 Marine Ecosystems

Excellent small scale and large scale projects have been run in marine ecology. Many of their findings are summarised beautifully in Branch and Branch (1986); they involve studies of Cephalopods, Sea Invertebrates, Marine Mammals, Sea Birds, Seaweeds, Pelagic Fish, Demersal Fish, Marine Linefish, as well as the physical and chemical factors in their marine environment.

19.4.1 Small Scale

Conditions vary very much depending on the situation considered. The differing environments are (references here are to articles in the survey volume: FRD 1990),

(a) rocky shores (Branch),
(b) sandy beaches (McLachlan), involving also coastal dune dynamics,
(c) estuaries (Whitfield),
(d) open sea and shallow sea floor,
(f) deep sea and deep sea floor.

Areas of marine biology that have developed strongly are rocky shore ecology and in particular the role of different types of competition in regulating community structure, compared with the role of predation and of physical forces such as wave action (Branch) and sandy beach ecology where Brown and McLachlan have come up with a new classification scheme for sandy beaches based on relative exposure to wave action. The importance of phytoplankton in recirculating cells of seawater in the surf zone has also been demonstrated by McLachlan.

Thus good quality work has been done in each of these areas, except deep sea, left largely untouched because deep sea research is very expensive. However it is also very interesting: it is, as has often been remarked, the last unexplored frontier on earth.

A particularly successful project was the Kelp Bed Programme, which became the forerunner of the Benguela Ecology Programme.

19.4.2 Biome Research: Benguela Ecology Programme

The Benguela Ecology Programme (BEP) is a highly successful research programme studying the food webs and ecological basis of the west coast fishing industry, e.g. anchovy, pilchard, hake, squid, mackerel, and rock lobster. Initial success included resolving the spawning pattern and migration routes of pelagic fish in relation to the physical environment and current patterns on the Agulhas Bank and west coast.

The success of the BEP is related to it being able to capitalize on cooperation between government departments and the academic environment of Universities and museums, utilising the strengths of the former in providing resources, logistic support and practical problems, with the latter providing enthusiastic young researchers anxious to cut their teeth on real problems. The unique position of South Africa in relation to the warm Agulhas current on the south coast and the cool Benguela upwelling system on the west coast, place South Africans in a better position to resolve the problem of variable recruitment than almost any other fishery in the world. The interaction of the two current systems creates large variations in the physical environment, some of which can be detected from satellite images. Thus rings of warm water break off the Agulhas current and invade the west coast influencing weather and fisheries for weeks to months.

By studying and understanding these influences, one expects to get closer to understanding the effects of larger scale, longer lasting variations such as the El Nino Southern Oscillation (ENSO). At present mathematical models are being developed to serve as a basis for optimal harvesting on a statistical basis. As we understand natural environmental effects better, it should be possible to use predicted scenarios of El Nino's and other fluctuations to predict when it is safe to allow heavy exploitation of fish stocks, and when it is necessary to cut back on catches because of anticipated poor spawning or recruitment. It is anticipated that expert systems and rule-based models will play a role in future fisheries management.

Excellent reports of the first two phases have appeared (Payne *et al*, 1987; Payne *et al*, 1992), and the third phase is presently under way, focusing on anchovy, sardines, and squids, with the aim of understanding factors causing variability in of each of these populations and improving estimates of this variability.

In Phase III, working groups are looking at:

(i) physical processes and remote sensing,

(ii) biogeochemical processes, including primary production studies,

(iii) zooplankton and recruitment of pelagic fish,

(iv) factors affecting the distribution and variability of anchovy and sardine stocks,

(v) factors affecting the availability of and variability in abundance of chokka squid,

(vi) long term trends in the abundance of dominant resources in the Benguela ecosystem,

(vii) variability of pelagic fish and squid and the environment,

(viii) stock assessment,

(ix) resource management.

Details of this ongoing work are given in BEP (1992).

19.5 Antarctica

SA biological research in continental Antarctica, on sub-Antarctic islands, and in the sub-antarctic zones of the southern ocean contributes to a suite of international programmes. These programmes deal with four principal topics: management of the exploitation of renewable resources; evaluation of the biological consequences of enhanced UV-B radiation; evaluation of the effect of chemical pollutants; and evaluation of the biological effects of the phenomenon of global warming. These evaluations involve populations of plants and animals, as well as the functioning of ecosystems. In addition, several research projects are aimed at obtaining an improved appreciation of how selected plants and animals respond physiologically, behaviourally and anatomically to a relatively harsh environment.

19.6 Policy and Priorities

We have a basic strength in this area that is internationally recognised. The topics considered are of fundamental importance in that they underlie conservation efforts, long term resource management, and sustainable farming policy. However a review of what has been achieved shows that its primary aim has usually been in the areas of plant and animal conservation, and of marine resources management. An exception was the Fynbos programme, that was concerned with biome rather than just species conservation.

There are several important areas that have been relatively neglected and need development, sometimes as a matter of urgency. In view of the special status and high cost of the Antarctic research station, we discuss it separately below.

A major problem with all the biome projects was the absence of any focus on issues relating to a developing world. Indeed the emphasis was entirely on 'First World' science as appearing in the pages of *Ecology*, *Journal of Ecology*, *American Naturalist* and other prestigious primary journals with a theoretical bias. Thus although this era provided a great stimulus in training postgraduate students in terrestrial ecology (including aspects of applied ecology), little of the *experience* gained is applicable to problems in the developing world. However this era forced the ecological community to think critically and develop skills which can be harnessed more appropriately, i.e. directed towards solving problems in developing areas.

The need is to maintain and even build our strength in ecological studies (and the different disciplines that are its component parts), but to a substantial degree with a shift in emphasis, taking the following points into account.

19.6.1 Biological Systematics

The issue of systematics has been raised above in various places, but it is in the ecological context, in regional-specific biological and ecological work, that its importance becomes apparent.

a) Many taxa are virtually unstudied anywhere in Africa (lots of insect groups, for instance);

b) We do not yet have anything even vaguely approaching an inventory of African biodiversity; we do for odd areas of special interest, but nothing even at the regional scale;

c) We know very little about the biogeography of African organisms except for flowering plants and vertebrates (probably $< 10\%$ of the total number of species);

d) the same is true for the community compositions of organisms in most ecosystems, particularly aquatic ones.

In other words, we do not have even the most basic "postage stamp" catalogue of the data concerning biodiversity, let alone the framework for understanding how it works. This is perhaps one of those fields that could be tackled with colleagues further North in Africa, because it does not require (although it could use) sophisticated or expensive equipment.

19.6.2 Subject Studies

Of the five fundamental components of ecology (weather, plants, animals, soils, water), four have been studied in depth but one - soils - has been relatively neglected.

Work on soils in SA has largely been based at agricultural research institutes rather than in departments of ecology. It has mainly concentrated on physical properties. For example at Elsenberg, work is going on in the following areas:
(i) methods to analyse plant-available nitrogen, phosphorus, potassium, sulphur, boron, molybdenum, and copper in soils;

(ii) the nitrogen mineralisation capacity of major soil types;

(iii) to determine the optimum level of soil phosphorus and potassium for crop production;

(iv) on the use of rock phosphate and the enhancement of its solubility;

(v) waterbalance studies of the major soil types when planted with the most important annual crops;

(vi) the influence of cultivating practice on the physical and chemical nature of soils.

These are significant topics. However what is largely missing in the overall balance is studies of *soil ecology* and *soil microbiology,* both fundamental to the biological functioning of soil. Issues in soil and water management identified as important in Africa include, research on maintenance of soil fertility, particularly the economics of minimum vs. optimum levels of fertiliser, minimum till, etc.; research on soil micro-organisms, especially mycorrhizae, and their role in plant nutrition under natural conditions and with various fertiliser treatments. The latter aspects have been neglected in SA. We seriously lack microbial ecologists in SA (by this topic we mean understanding of the ecological requirements, interactions and effects of free-living microbes).

Thus research in soil science in general, and in these areas in particular, should be strongly encouraged, as should informal sector and school research programmes related to all aspects of soil science.

In terms of the botanical component of ecology, one could suggest more research should be carried out at universities on scientific aspects of management of economically important plants than at present. Some good applied research was done in all biomes, particularly:

- fire management and wildflower harvesting in fynbos,
- water catchment management and alien plant control in fynbos,
- bush encroachment in savannah.

However we have not approached the level of applied research evident in Zimbabwe.

Additionally, important components in ecology arise from environmental geochemistry and environmental geophysics. The first subject is well developed, the less perhaps less so. Consideration should be given to more work in this area.

19.6.3 Area Studies

In SA, as mentioned above, there has been a focus in ecological work on natural systems and conservation-related studies. But in view of the situation in the country, we need studies of agriculturally important systems on the one hand, and socially important areas (urban ecology and rural ecology) on the other.

(a) *Forest ecosystems and agroforestry*
Although there is only a small percentage of South Africa covered by natural forest, many forests are poorly known. Few management guidelines exist. Even the topic of harvesting of forest products has only received adequate attention in the Knysna area.

Part of the problem was institutional; few forests are near universities and most forests "belonged" to various government departments and these departments tended to guide the research in these forests. Naturally this resulted in a restricted and parochial vision of appropriate research. What is needed now is a dynamic view of forest ecology, utilisation and management. The old approach of fencing-off areas to reduce disturbance is neither appropriate politically nor biologically. Fenced-off areas became squatter camps for displaced people. Ecological processes which depend on disturbance, such as may be inflicted by fire or by elephants, may be crucial for forest conservation. Appropriate levels of disturbance by people and other biota in general needs further attention.

Thus research on forest ecology should be developed considerably, with an emphasis in particular on understanding the potential of agroforestry projects. It is encouraging that Forestek is taking a lead in this area.

(b) *Farm Ecosystems*
This is a very varied and interesting subject, because there are many forms of farming (large scale and small scale; many different crops; many types of animals). Furthermore this is an important topic for our future. The need is to develop appropriate management policies and strategies to allow long-term sustainable farming.

There has been a great deal of research on the ecology of veld use by domestic livestock, much of it of high quality. However the great bulk of it deals with commercial farming, and ecological studies of subsistence farming are in their infancy. Nevertheless a start has been made with issues of the Grassland Society Journal devoted to the problem. There is considerable potential for an increase in work studying the ecology of long-term sustainable farming.

(c) *Wetlands and Inland waters*

We need more work on wetlands countrywide, even if of a very basic nature. It is a very big hole in our knowledge of aquatic diversity.

In terms of inland waters, a number of issues should be pursued:

i) *Databases*: the construction and development of chemical and biological databases that can be used for conservation, management, and GIS is underway. The maintenance of such databases is a very real need. there is little more useless than an outdated, messy database.

ii) *Monitoring*: If SA's water resources (and hence aquatic natural ecosystems are to be conserved and properly managed, a detailed, effective monitoring network will be essential. It must be far more than someone collecting data; if the data are not linked to a feedback system, then one is wasting one's time.

iii) Systematic work on *aquatic organisms and microbiology*, in particular obtaining a better understanding of the tolerances and requirements of SA riverine (and other aquatic organisms): regional differences, and the similarities/differences between ours and those from the Northern hemisphere (where most of the work has been done). This is important for water quality guidelines.

This is an area where we can develop good links with the rest of Africa. We have expertise here that is unique in Africa, which has had too much 'expertise' imported from Europe and North America, where ecosystems, problems, people, and solutions are different. That is, SA can offer an Afrocentric rather than a Eurocentric viewpoint.

(d) *Desertification and Degradation*

It is clearly important to establish the true situation in regard both to desertification and to degradation of farming areas, particularly in subsistence farming areas, so efforts in this direction need support. This is an area where collaboration with the rest of Africa could prove most fruitful (cf. AAS 1989).

(e) *Homeland and Township ecology*

Finally there are many densely populated and very degraded areas in the 'homelands' and in our urban areas, particularly squatter camps and large townships. The need is to study the present environment and ecosystems and the ways that restoration could take place (from an ecological viewpoint). This links up well with work the MRC is doing in their National programme on Urbanisation and Health.

Given this variety of problems to be tackled, and the variety of different ecosystems in different parts of the country, it is essential to establish solid ecological research country-wide. Thus we need local centres of excellence in the subject in each area, each working with an emphasis on tackling the important local problems, but networking with the others in order to understand the national patterns of problems that emerge from the studies.

19.6.4 Global Change

Because of the potential importance of its impact, we need to continue interdisciplinary programmes on monitoring of global change and on its impact on our terrestrial ecosystems. Monitoring and predicting these changes - a major concern of climatology - involves field observers, satellite observations, upper atmosphere physics and space physics, palaeoclimatology research (based on geological and palaeontological observations), and the interlinked topics of meteorology and oceanography.

Because of the environmental and climatic links between Antarctica and SA (Lucas *et al* 1991), a SA research programme in the Southern Ocean is of significance (Lucas *et al* 1993); it also makes a contribution to the Scientific Committee for Antarctic Research (SCAR) and other international programmes concerned with climatic change. Considering the effect of the changes on our ecosystems is a topic for ecology.

19.6.5 Antarctic

To exploit our proximity to the Antarctic, there is a good case to continue the Antarctic base SANAE (and supply ship), and associated research activity. This is an significant multi-disciplinary facility, that is useful in terms of the issue of global warming, space physics, and biological studies, and enables us to take part in a series of international conventions. The space physics research is of particular significance in terms of the data it provides related to the upper atmosphere. However this is also an expensive project, and its continuation needs careful evaluation, taking into account other benefits that accrue to us from running the base as well as those of a purely scientific nature. The base has a significant political role, in terms of establishing a South African presence in the Antarctic; indeed South Africa is a signatory of The Antarctic Treaty, and has some obligations as a signatory that include facilitating scientific cooperation within the Antarctic Treaty area and providing scientific advice to SCAR (the Scientific Committee for Antarctic Research).

In 1992 the Antarctic re-supply vessel SA Agulhas was upgraded at a cost of about R20 million. Most of the money was spent on improving the scientific capabilities of the ship which has made it competitive with international first-world research vessels. We can now put about 35 scientists to sea with modern facilities. Although the cost of running the ship is high, the science component is almost always tagged onto a logistical re-supply voyage to SANAE, Marion Island or Gough Island. A "wild card" here is the role of the navy in a new South Africa. They have assisted logistically in the past, and it is possible they would like to play a greater role in this sphere.

The cost of the new base, to be built on solid rock, is estimated to be about R34 million and it should have a life-time of at least 20 years or more. The base is necessary to replace the existing base which is about 60 feet under the ice-shelf and is being crushed and is now dangerous.

The Antarctic programme is perceived to be expensive and therefore a first world luxury. This perception is not entirely accurate. The programme is funded by the Department of Environment Affairs (DEA). For 1992/93 the total DEA budget was R236 million. Of this, the Antarctic and Islands Programme received about R16 million or 6.8comparison other DEA funded programmes received the following in millions of rands–

National Parks including the Nat. Bot. Inst.	84
Weather Bureau	44
Marine Development (Incl. SFRI)	39
Logistics	34
Antarctica & Islands	16
Administration (DEA)	15
Pollution Monitoring	04

The Antarctic & Islands budget can be further broken down as follows–

Logistics	11.8
Science	04.2

The science budget is split up between four programmes—

Physical Sciences - atmospherics	1.23
Oceanographic Science	1.12
Earth Sciences - geology	0.63
Biological Sciences - terrestrial, avifauna	1.01

The balance between this total (3.99) and the total (4.2) is made up of scientific expenditure incurred directly by DEA.

For 1993/94 the Antarctic & Islands budget is inflated to R34 million because of the associated costs of building the new base over the 1993/94 and 1994/95 summer field seasons. The breakdown looks like—-

Upgrading / replacing helicopters	15.0	
Helicopter spares	2.6	
Fuel	2.0	
Capital equipment (Snow tractors etc.)	7.2	
Sea-time on SA Agulhas (SANAE)		
V.70 1993 106 days	3.8	
Sea-time on SA Agulhas (STC)		
V.72 1993 44 days	1.5	
Science Programmes	4.2	
Oceanography		1.12
Physical Sciences (Atmospherics)		1.23
Earth Sciences		0.63
Biological sciences (Terrestrial)		1.01

Other Costs (Thousands of Rands)	
Meetings	100
SAJAR (2 vols.)	25
Clothing per person	3
Salary increases	89
Packaging	30
Food, SANAE, per year	500

Continuation of this programme will undoubtedly come under scrutiny. It is clear from the above that it has a range of scientific benefits in various areas, enabling us to take part in a series of international programmes and collaborations, as well as providing political and diplomatic benefits that lift the decision from a purely scientific one to one with other dimensions. The scientific benefits are sufficient to make a considerable case for its continuation from the scientific viewpoint.

19.6.6 Education

This extension of ecological research country wide should be tied in to school education programmes, preferably involving research projects (regarding plants, birds, weather, water, and soil) as suggested above in relation to botany, zoology, and meteorology.

19.7 Equipment

The equipment required has already been discussed under the component subjects. The particular needs, apart from analytic tools (e.g. to determine chemical element composition in the soil, and plant- or ocean-atmospheric gas interchange), are for remote sensing, field stations, and ships.

Chapter 20

Environmental Studies

Environment: the sum total of biological, physical and chemical factors in some area. Ecosystem functioning depends on the environment providing suitable living conditions for organisms in that area.

The concern of *Environmental management* is the optimal management of environments, preserving both their short-term and their long-term viability and habitability, while providing materials and living space for humans and animals. This involves protection of the environment from a wide range of pollutants and disturbing factors, conservation of renewable natural resources, and protection of species and genetic diversity. Because of the essential role the environment plays in terms of providing the resources we need for living and for economic development, and the waste output that such resource use inevitably implies, the subject is inextricably intertwined with that of long-term *resource management* and optimal use of non-renewable resources.

Environmental studies researches environmental conditions and the best ways to plan environmental management. This involves understanding the ecosystems of the area and its relation to the natural environment, implying the scientific aspects of management; but as it involves planning aspects it necessarily involves also some of the social sciences, particularly economics, and law. It is closely related to developmental studies, economic geography, and urban and regional planning.

20.1 The Present Situation

Among the most urgent and the most threatening current problems of the Southern African environment are a burgeoning third world population, over-exploitation of renewable resources such as marine fish, despoliation and habitat destruction of the ecologically sensitive coastline, and environmental decay in rural areas and crowded urban settlements (all of these driven by population growth). There is a longer term concern over global warming and climate change.

Aquatic ecosystems are under the most severe threat of all. Freshwater aquatic ecosystems are both the containers of water as a resources (the most limiting of all resources in SA) and are resources in themselves: they contain living organisms (e.g. fish) and also (because of the organisms) they clean water, and so provide a service to humans. Their status is therefore of utmost importance.

We need informed policy decisions on all these matters, based on sound environmental analysis. A detailed overview of most of these issues is in Fuggle and Rabie (1983), hereafter referred to as FR. The global and local context, and the overall SA issues to be addressed, have been reviewed succinctly in Huntley *et al* (1989). A more detailed sectorial analysis with specific sector policy guidelines has been given by the Environmental Monitoring Group (Western Cape), see EMG (1992).

20.2 Environmental Management

In considering environmental management, there are two kinds of conflicts to be taken into account, in addition to the variety of technical solutions possible for any particular problem.

(a) There is a fundamental opposition between exploitation and conservation, that is, between long and short term interests. The demand for exploitation of resources is driven both by population growth and by the demand for increasing equity in SA. The question is how to balance pressing demands against long term interests.

(b) In any particular situation there will usually be conflicting interest groups and conflicting priorities; a specific policy choice will satisfy some people but not others.

For both reasons, decisions cannot be made on scientific or technical reasons alone (even if this were feasible politically). Scientists can provide information but policy decisions must be made by people as people. Scientists have no special rights in this regard, but they do have a responsibility to inform the public as to the nature of important issues facing us. The question is how to proceed.

20.2.1 The Planning Factors

The factors that come into consideration are,

1) *Scientific/ecological*: what is scientifically possible. It is here that a sound analysis based on ecology, including applied natural sciences (environmental physics, geophysics, chemistry, and geochemistry), is a necessary component of any decision.

2) *Environmental economics*: what can be afforded and what gives best value (FR Chapter 5). This is where economic data is needed (prices, interest rates, subsidies, loan conditions, etc.) and the assumptions of welfare economics enter (FR section 5.3.1), as well as criteria for what is an improved situation (FR section 5.3.4). Resource economics is vitally important.

3) *Environmental psychology and sociology* (personal and societal preferences) affect one's choice of these criteria, as do

4) *Environmental philosophy and ethics*: one's world-view (see FR section 1.4, and Barbour 1993, Chapter 3).

Furthermore planning is affected by

5) *Environmental politics*: the political programmes and power groups that have influence over environmental policy.

Another important element is

6) *Land and property law, water law*: who owns what, and what rights do they have in terms of what they can do with it (FR, Chapter 19).

Finally one must consider

7) *Implementability of the decision*: how will it be implemented, and will this in fact succeed.

The fundamental point is that all these elements inevitably enter: so one cannot adequately deal with environmental issues without becoming to some extent involved in the human sciences (Stauth in FRD 1990).

20.2.2 Methodology: Enabling Proper Decisions

Given this complexity, a subject of research in its own right is *the nature of the decision-making process*, which is an example of Multi-criteria Decision Making (see the section on Statistics). Various approaches are possible.

One is a 'Delphi'-methodology (Stauth 1983) that involves carrying out an environmental evaluation (FR, Chapter 21), and then presenting to interested parties a set of alternative possible decisions and their economic and environmental consequences. Because of many uncertainties that arise, there is usually a need to present alternative scenarios for what can happen (cf. Huntley *et al* 1992).

In this process, the factors 3) and 4) above are to a considerable extent dealt with implicitly through deciding what range of factors will be included in this evaluation and the weighting their relative importance, both done by a process of consultation and consensus building, which is also used to obtain a final recommendation. Factor 5) is the basis of selection of who is involved in the consultation.

Thus if this approach is adopted, it is factors 2) 6) and 7) that have necessarily to be explicitly taken into account in the decision process. Hence research into environmental management has to explicitly include *environmental economics* and *property and water law* (including issues such as who has control over the sea, over resources underground, over water, and over air above the ground) as relevant topics. Resource economics is centrally important here.

Whether or not this approach is adopted, it may be helpful additionally to explicitly study the other social science topics mentioned above (factors 3, 4, 5); for this may assist in generally understanding the broader aspects of environmental issues and management. For example the St Lucia Bay environmental impact study has commissioned sociologists to comment on the sociological impact of developmental proposals. An important issue then is obtaining agreement on foundations and methodology to be used in such social science research in this applied setting, and the extent to which the different factors mentioned (psychological, sociological, philosophical, etc.) should be taken into account.

20.2.3 Methodology: Implementing the Decisions

Given the decision as to what should be done, its implementation (factor 7 listed above) implies decisions about and involvement in,

a) *Environmental law* (FR Chapter 4), in particular land use planning and control (FR Chapter 20) plus specific laws relating to each topic (air pollution, hazardous waste management, and so on).

b) *Official administration and policing of environmental affairs* at all levels (FR Chapter 6), which can be done in many ways and styles; and perhaps

c) *Voluntary organisations* concerned with the environment (see FR Chapter 7).

Thus another area of research is *optimal ways of implementing decisions that may be taken* (which in fact helps determine which is the best decision). This clearly links in to organisation and management theory.

20.2.4 Methodology: Guiding Policy

To guide the whole process and give it consistency, this should all take place in the framework of an overall policy based on long term as well as short term concerns, and resulting in suitable policy guidelines providing a sound framework for environmental management. Thus a foundational field for research is *the best choice of such policy and guidelines*, for this is the basis of the rest of the decision-making process (and must take into account all the other factors above, in particular implementability). For example, Huntley *et al* (1992) give an overall policy framework, and (EMG 1992) contains a set of considered sectorial policy guidelines. A further important issue then is to what degree these guidelines should be implemented in legislation, and if so how best to do so (see FR for detailed sectorial discussions).

These general planning issues come into play in examining each specific environmental concern mentioned below.

20.3 Renewable & Non-Renewable Resource Use

Here we are concerned with the environment as the source of energy and materials for life and commerce. In terms of non-renewable resources, one is concerned with minerals (precious minerals, rare metals, construction materials) and coal, oil, gas. In terms of renewable resources, the concern is with water, crops, forestry, flora, and fauna. In each case research is needed into (a) the present state of the resource base, (b) methods of recycling, conservation, and optimal usage, leading to (c) a strategic plan for that resource.

Major surveys of these topics are in Baker (1976) and RSSA (1978). No such comprehensive overview has been given since then, but summaries are in FR (Chapter 3) and Huntley *et al* (1989). Particular resources are planned for by particular management groups, for example Water Affairs is doing catchment-based systems analysis and developing relevant policies, but an overall resource plan encompassing all major resources is lacking.

20.4 Environmental Degradation & Rehabilitation

Here we are concerned with the environment as the repository of waste and victim of exploitation. The main issues are (see FR, Section 1.2):

(a) *Pollution*: Degradable wastes, Persistent wastes,

(b) *Reversible biological and geophysical impacts* (road building, open cast mining, quarrying, etc.),

(c) *Irreversible biological and geophysical impacts* e.g., extinction of animals, plants, and fragile ecosystems.

The importance of this work arises because there is a hidden crisis in environmental health in many areas.

20.4.1 Land Degradation

This involves scars from mining and quarrying, soil erosion (FR Section 8.1), and decline of soil quality; together with pollution by solid waste

(FR Chapter 17) and biocides (FR Chapter 18). Research is needed into quantifying such degradation and into ways of handling it, in particular rehabilitation of old sites. This should include a study of the potential of trees to contribute to the rehabilitation of degraded rural areas and to enhance productivity.

Crucial is research into waste management and handling (toxic, non toxic, radio-active), including waste recycling or alternative use where possible. Environmental geoscience studies waste dumps and their interaction with geology, and physics research has a positive role to play in waste management (see e.g. Rose *et al* 1972). The role of social patterns is of importance here: for example a significant topic is consumerism and packaging (EMG 1992, see pp.51-56).

The other crucial area is soil conservation, both in terms of soil erosion and soil quality. Ecologically based management policies are needed here.

20.4.2 Water Degradation

This arises on the one hand in terms of marine pollution, with its implications for the marine environment (Lord in FRD 1990); and on the other in fresh water pollution (FR Chapter 14), in both cases inevitably involving effluent disposal and sewage. Interesting physical, chemical, and biochemical issues arise here. Water Affairs has guidelines for most 'users' but not for the 'environment'. A significant form of pollution is waste heat (e.g. in the discharges of hot water from Koeberg into the sea). The impact of waste heat on the local ecosystem can be very important.

20.4.3 Air Quality

The issue here is air pollution (FR Chapter 13), requiring atmospheric studies (composition, quality, pollution measures), determining the effects of such pollution, and researching remedial measures (according to the source). Physics is central to methods of reducing air pollution (e.g. by more efficient burning of coal) and chemistry in scrubbing emissions.

Particularly important is the contribution of carbon dioxide to global warming, and of Chlorofluorocarbons (CFC's) to upper atmosphere ozone depletion. Measures to reduce emission of CO2 and CFC's are therefore very important.

Air quality in SA is bad in many areas, particularly the Eastern Transvaal. A consequence is that there are acid rains in the Eastern Transvaal. Furthermore, the second most important cause of infant mortality is respiratory related diseases which are greatly exacerbated by poor air quality. Recent studies have shown strong correlations between poor *indoor* air quality (as a result of coal and wood combustion) and respiratory disease.

The Department of Health is poor in many aspects of air pollution: monitoring, control, and policing. This needs improvement.

20.4.4 Other Factors

The main other factors are radiation (FR Chapter 15) and noise (FR Chapter 16) where again measurement, impact, and remedial measures need to be investigated.

In all of these cases, SA has a solid basis of work going on, but its application is spotty and needs consolidation. In particular it is not directed enough to the rural ('homeland') and 'township' areas.

20.4.5 Waste Management

Much of this can be included under a general rubric of waste management: consideration in an inclusive way of how to handle the myriad waste products of our society, so as to reclaim as much as possible through various kinds of recycling, and to dispose of the rest (toxic and non-toxic) in a non-destructive manner.

20.5 Conservation and Protection

Here we are concerned with the environment as the basis of the ecosystem that maintains and enriches our life.

20.5.1 Conservation

The issue here is that of conservation of species and wildlife ecosystem functioning. This is a very well developed concern in this country, both in the case of indigenous plants (FR Chapter 9) and wild animals (FR Chapter 10). However in the overall context of the country, it has perhaps been handled in a way that has not taken socio-economic realities sufficiently into account. The theme is important, but must be put in its context and not indulged out of all proportion to costs and to other national needs.

Suggested conservation guidelines are given in EMG (1990), p.32-33, emphasizing the principle of local community participation in game and nature reserves. However non-reserve areas are also important - in fact more so, in that they aren't protected but affect people's daily lives far more.

An important focus in this work are the *Red Data Books* on rare and threatened species, which for example list 1326 rare and threatened species in the Fynbos Biome. At present far too few of these species are receiving rescue treatment. Proper research support is needed for this work, duly balanced against other goals.

20.5.2 Environmental Protection

The point here is to develop laws that work and administration that is practical in terms of protecting the environment, insofar as possible before any harm has been done. This requires careful analysis of the nature of the laws in terms of their ecological content on the one hand and their socio-political content on the other, and where possible employing the principle of feedback control in their design (Baxter 1974).

The challenge is an integration of the other themes mentioned above - land use planning, developmental control, resource management, waste management - into a workable system. Particularly one would like to see here taxation and subsidy systems that take waste-creation and entropy production seriously (Daly 1987).

20.6 Applications

The general principles need application on different scales: (local, regional, national, global); there is need for developmental control and resource management at each scale. Separate issues arise for each type of environment or ecosystem, in each case their study needing integration of the research of natural and social scientists.

20.6.1 Freshwater Systems

The concerns here are catchments and wetlands (FR Chapter 11). Catchments are important in how they impact on rivers. Wetlands are important in soil conservation, flood control, water purification, biodiversity. Because of their importance to water supply, well-developed policies are in principle at hand through the efforts of the Department of Water Affairs and Forestry.

20.6.2 Marine Systems

The concern is living marine resources (FR Chapter 12). The renewable resources of the sea could play an increasingly important role in the protein supply of poorer communities. The wise management of these resources to ensure their sustained production for future generations requires policies based on reliable knowledge. Such knowledge requires a solid body of environmental research in marine biology, coastal and estuaries management, physical and chemical oceanography, and fisheries science.

This has been the subject of intensive investigation in SA, involving studies of marine pollution (Lord in FRD 1990) and effluent disposal (Toms in FRD 1990), marine conservation (Robinson in FRD 1990), and fisheries management (Stander in FRD 1990). Nevertheless their implementation still leaves a lot to be desired.

It may be assumed that South Africa will soon, following international example, declare an exclusive economic zone in its adjacent oceans. This will add considerably to the surface area of the country. The new area, its geology, its sediments and its potentially exploitable resources are very poorly known. The marine geosciences in South Africa therefore require special support to carry out the required investigations. There are also untapped Antarctic sea resource possibilities, for example krill, that can be explored.

20.6.3 Coastal Zone Management

The coastline of southern Africa plays an important role in such fisheries as crayfish, in mariculture, and increasingly as an economic asset in international tourism. With increasing pressure of the population on this limited resource, extensive ecological research is required in support of informed decisions on coastal research management, to inform optimisation of a resource which has great tourist potential. There is at present a problem of coastal and estuaries environment deterioration, which needs to be addressed.

Research in this area is reasonably well advanced (Heydorn *et al* in FRD 1990, Bruton: 1992) but the management side needs development. Particularly important is estuaries management, because of its role in terms of sea life ecology. It is encouraging that proposals are in place for the formulation of a coastal zone management policy, to be implemented soon. The intention is that there should be extensive community consultation in order that the policy be broadly acceptable and effectively implementable.

20.6.4 Terrestrial Systems

There are a variety of ecosystems that need consideration: Karoo, fynbos, savannah, urban, large scale farming, small scale farming, forests. An overall policy needs to ensure that adequate planing and management knowledge exists for each major such type of situation. At present we have great expertise in limited areas, particularly nature reserve and wildlife management; this needs to be extended to all the other areas in a systematic way, building on adequate ecological understanding of each biome. The way that such understanding influences management policy may be seen for example by the debate on Karoo grazing systems (Hoffman 1988).

20.6.5 Global Environmental Change

Our contribution to understanding the causes of global change has been mentioned above. The issue here is how to handle its consequences, in particular in coastal areas, as well as in terms of adapting to changing rainfall and climate patterns.

The need is to monitor changes as they take place, for example rising sea levels and temperature changes, and to develop suitable policies and responses based on our understanding of the impact of sea level rise and climate changes. This requires modeling of the future climate effects and ecosystem impacts, as well as policy development. To some extent this is under way already.

20.7 Policy and Priorities

We have a sound basis for environmental studies and management in this country, but it needs extending in its scope.

20.7.1 National Environmental & Resources Audit

We need a comprehensive and authoritative study that will reflect the nature, distribution, values, and state of health of all natural resources - a balance sheet of what is available, and guidelines on how interest on this capital can be sustained.

The information is largely available: the issue is to draw it together synthesis and interpret it. As well as university and government department research, every major corporation in every major industry should do its own environmental review. Then the need is for an audit process and the integration at the level of information on major national resources (air, water, soil, flora, fauna). This would indicate where the environmental problems really lie, and facilitate delegation of environmental responsibilities from central government to individual industries and local authorities.

20.7.2 Environmental Evaluation Units

We need groups situated in each major region of the country, each with the ability to carry out effective integrated environmental management investigations and policy proposals. There are indeed many Environmental Impact Units, but they are not necessarily carrying out the work required. Two issues arise.

The first is whether they should be private (as at present) or not. The second is certification, not for the sake of bureaucracy, but because those giving such advice must have the technical qualifications and training needed: they must adequately understand the ecosystems they are giving advice about, which in turn demands a basic training in physics, chemistry, botany, zoology, geology, and their interactions in the functioning ecosystem.

The SA Institute of Ecologists is an unofficial certification body that understands the needs in terms of skills. The SA Natural Council for Natural Scientists is the official certification body, but does not recognise the need for integrated training!

20.7.3 Full Range of Concerns

Additionally, the management investigations must be complete in terms of subjects considered: adequate consideration must be given to the legal, economic, social, and political aspects, as well as the technical ones. This means firstly that research in these areas must be undertaken, and in the methodology of environmental decision taking; and secondly that the individual units must have the capacity to handle the full range of issues.

This is a tall order in terms of abilities of any individual. Thus the practical course will be to staff the units with a team of people who are each expert in one or more of the needed particular subject areas, so that the group as a whole covers all the necessary skills, and who are able to work well together as a team.

In particular, resource economics is vitally important, but not well developed in this country. This is a real gap and a real need in SA. Special effort should go into its further development.

20.7.4 Environmental Projects

As well as the major scientific research projects, one should encourage a series of community based environmental educational and upliftment projects. An example are township tree-planting programmes, resulting in tangible benefits by providing fuel, food, shade, shelter, and aesthetic benefits, while helping to protect the soil.

The aim should be to initiate such efforts and then build them up into integrated projects concerned with:

- local environmental and resource audit,
- local resource conservation and management,
- local environmental conservation and rehabilitation planning.

These should have a strong community base and aim as far as possible at encouraging local job creation and skills building, in the spirit of the Appropriate Technology movement.

Much of this work could be built into integrated school projects at the senior level, provided there is adequate advice, guidance, and quality checking available from local or regional Environmental Evaluation Units (mentioned above), which would have to be in charge of integration of the research done. Each project would thus be seen both as worth doing in its own right, and as a contribution to environmental education in the community and in the schools.

20.7.5 Traditional Knowledge

This should take into account the importance of understanding traditional knowledge systems and practice in relation to woodland and natural resource management (including the resilience of woodland and its ability to recover and be productive), and their potential for informing sustainable rural development policies. Botany needs to interact with anthropology, environmental sciences and agricultural economics to advance a multi-disciplinary understanding of this area.

20.7.6 International Cooperation

On the other end of the scale, we should continue to take part in international environmental research projects, in we are already playing a significant role. The major challenge here is to set up meaningful collaborations within Africa; this is already starting.

20.7.7 Environmental Protection Agency

This document is concerned with research rather than management. However it does not make sense to carry out environmental research unless this is likely to have some effect of what actually happens. A key element here is that SA needs some sort of Environmental Protection Agency.

At present the DEA lacks funds and credibility. Ironically DWAF, whose brief is to provide water, is also acting as the guardian of the country's aquatic ecosystems (and is trying very hard too), and is thus developing a kind of corporate split personality.

This is neither 'fair' nor appropriate - nor in the long run does it bode well for conservation.

20.8 Equipment

The main need here, apart from measuring and analytic equipment for environmental physics, chemistry, and geology, is (a) ground and sea observation stations, and (b) remote sensing data, in particular access to satellite observations of the atmosphere and resource surveys (Falloux 1989). It may even be that remote sensing is sufficiently important that research in remote sensing should be recognised as an interdisciplinary topic in its own right, with a dedicated research unit assessing what is being done in this area, and what could be done.

E: Interdisciplinary research

In this section we consider some further research areas that are based on or are important to science, but (like environmental studies) have an essentially interdisciplinary nature. It must be emphasized that what follows is not a comprehensive review of research in any of these areas, which is not possible within the confines of a document of the present size. Rather it is an impression of the scene in each case as seen from the science side, and some comments as to how one might possibly strengthen research in these areas by a science input. We recommend a much more thorough analysis of the present situation and possibilities in each case, with the following comments taken as indications of some directions one might follow up.

The topics considered here are, 17: Applied Science, 18: Community Science, 19: Human Ecology, 20: Human Development, 21: Brain and Cognition, 22: Policy Research. It is clear also that some topics that follows are not strictly 'science'; we feel that nevertheless it is important they should be mentioned here, either because they have strong science components, or they are of importance in the application of science.

We only give brief notes on these subjects; each should in due course be developed into a fuller analysis and policy proposal.

Chapter 21

Applied Science

Scientific understanding underlies proper development of Engineering and Technology, Agriculture and Forestry, and Health and Nutrition in the modern world. These are considered in turn. Other applied science topics are not considered here, notably Weapons and Defence.

21.1 Engineering and Technology

Perhaps partly as a result of the authoritarian nature of the apartheid period, and partly as a result of a colonial mentality which has favoured imported technology over the encouragement of local developments, many large scale engineering projects have been carried out in ways which have not, on one hand, involved adequate community and political consultation, and on the other, have not led to the transfer of technology to local sources. In many cases, the combination of these factors has led to less than optimal solutions, in the technical, economic and social senses.

There is increasing recognition of both of these factors in industry and in the funding agencies, and the degree of interaction between, for example, industry and the university engineering departments has grown very significantly in recent years. This growth was fuelled initially by strategic projects which were affected by sanctions, and was thus subject to artificial restrictions and constraints; however, the contribution of local technology to international industrial competitiveness and the contribution of community input to infrastructure development are factors which are now widely accepted.

The development of innovative local technology depends crucially on multidisciplinary activity, in part because South Africa cannot generate critical size groups in highly specialised fields, and in part because innovation will flourish only when a wide range of perspectives are brought to bear on the problem. The science community has so far been only marginally involved in this increasing industry-research interaction. It is imperative that such collaboration be encouraged and nurtured. Similar comments apply to a range of the social sciences.

21.1.1 Policy

It would therefore be appropriate to set up a group that looks at the benefits of such interdisciplinary research as well as ways and means of encouraging it and funding it (cf. Smith 1984). This should include consideration of how to include an appropriate social science input.

Cooperation between the academic and non-academic sector can ultimately only be fostered through personal communication and the development of a culture of contact and exchange between academia and industry. However on a logistical level interaction may be promoted by some appropriate infrastructure in the universities and the organisation of workshops covering areas of application (transport, housing, information issues for example) or specific problems arising in chemical, electrical, civil, or mechanical engineering.

As takes place regularly in the faculties of engineering at the universities, encouragement should be given to the interchange of personnel between university science departments and industry. This could be enhanced by applied courses at the tertiary level where joint teaching takes place (people from industry give sections of the course), applied science projects in industry are undertaken (where people from academia analyse the practical issues from their distinctive perspective) and by the involvement of scientists in continuing education courses for industry.

This is fully in accord with the needs seen by the Consultation of the Management of Science for Development in Africa (Odhiambo and Isoun, 1988), cf. the summary in Section 4.2 of this document.

21.2 Agriculture and Forestry

As has been emphasized above, agriculture is an important sector of the economy, and there has been good research work in the ecology of veld use by domestic livestock but little in the area of subsistence farming. Forestry has, at times, equaled agriculture as an export earner and is an important industry for self-sufficiency in construction materials. Good research work through Forestek has contributed to the industry's success. However in both agriculture and forestry, in striking contrast to the case of fisheries and game parks, there is rather little cooperation with strong science university departments that could make a major input.

A considerable amount of money is spent on research through the Agricultural Research Council, but it appears that most of this is routine rather than innovative. An exception is a small but solid initiative in the field of biotechnology that shows considerable promise. Veterinary science is relatively strong.

21.2.1 Policy

The case for technical research is similar to that in the previous case, and the policy is essentially the same. A group should be set up that looks at the benefits of interdisciplinary research into agriculture and forestry, as well as ways and means of encouraging it and funding it. This should have a primary emphasis on developing sustainable agriculture (Reganold *et al* 1990), and consider how to include an appropriate social science input, particularly in relation to farming in the 'homeland' areas, where issues such as land tenure and sharing of resources (e.g. tractors) are crucial. Land and water management practices as much as developing better, environment friendly crop health management practices must be developed, using new biotechnology tools to support improved stress resistant plants. The urgency in this need arises because the SA population will almost double in the next two decades.

This is in agreement with needs seen in the rest of Africa. Dow (1986) identified the following institutional requirements there:

1) Strengthening of agricultural research capabilities so that they may be devoted to improvement of traditional farming systems.

2) Extensive support and upgrading of agricultural faculties and colleges is required for high-quality technicians to carry out research development

and extension services.

21.2.2 Specific Themes

Many of the agricultural themes that should be looked at by such a group have been discussed in Part I. A few specific points:

* There is a need to research improving the accuracy of weather forecasting and integrating this into agricultural planning systems;

* As mentioned in previous sections, there is a need for a powerful interdisciplinary research approach to soil science and soil care (cf. Lal 1986, Dommerges 1986);

* Academic and applied work on plant-pest problems and biological control should be encouraged, including biotechnology techniques;

* Agroforestry is seen as a very promising development elsewhere in the world (see Douglas and de Hart 1976, Okigbo, 1986; Kerkhof 1990), so research on its nature and implementation, particularly the ecological and economic aspects, should be encouraged (and is already underway, see Forestek 1994);

* Similarly there is a need for research on integrating livestock into cropping systems for mixed farming (Tothill 1986);

* Irrigation: we need research on small-scale supplementary irrigation possibilities (possibly micro-computer controlled).

21.2.3 Cooperation with Africa

This is an area where very strong links should be built up with the rest of Africa, resulting in a two-way flow of knowledge and expertise. One might especially take cognisance of research priorities in the rest of Africa, and consider joint major international research projects focused on them, similar to those that have been undertaken in studying ecology and the environment under the IGBP.

As an example, a considered statement of research needs by Michael Dow (1986) identifies the following as research priorities:

1) Development of plant cell and tissue culture techniques which enable disease-free cultivars or elite stock of food crop, forage shrub or tree species to be produced with reliability and cheaply.

2) Techniques for embryo transplant and related advances in handling of livestock genetic material which can speed up production of elite herds of animals by as much as 100-fold over traditional breeding methods.

3) Identifying and producing inocula of soil micro-organisms that work closely with plants in extracting nutrients from difficult soils, making formerly unproductive regions into rich agricultural areas.

4) Availability of relatively inexpensive computational facilities, even at the farm level, enables a degree of improved management of farm activities, provides a powerful research tool, and above all the ability to model and predict the outcome of alternative courses of action that provides means to improve planning and management of agriculture at the national level. In the short run this ability is believed to be capable of improving agricultural output equivalent to the long-run contribution of biotechnology.

Joint research programmes in which we co-operate with other countries in Africa could focus on one or more of these issues. It is encouraging, then, that the Science councils already have programmes for international cooperation and strategies for involvement in Africa, as a basis for such development.

21.2.4 Community Research Projects

One of the most important factors in meeting the needs of local farmers - and of making the results acceptable to them - is that the research projects have a community involvement as well as technical component.

Suitable consultative forums should act as meeting places where the kinds of problems faced and possible technical assistance each discussed, and mutually agreeable research programmes set under way, with some local farms being used to test and demonstration research findings. Part of the aim is to involve community members as active research participants. It is most encouraging then that for example Forestek are already involved in this kind of consultation (Forestek 1994). This approach could involve school research projects which, as in other cases discussed above, provide valuable data while also having a major educational component.

21.3 Health and Nutrition

Fundamental and applied medical research is very strong in SA, and much of it has a strong science base. Health care and nutrition is also well understood (in principle). However interdisciplinary research into community health is much less developed, although some new initiatives in this area have been taking place in the past decade (with a strong epidemiological and statistical component). The management concepts of Essential National Health Research (ENHR) adopted by the World Health Organisation for developing countries, and adapted by the MRC for our country, provides a basis for future work which is in accord with the ideas in this document.

The issue of high-tech, high cost health care is a controversial one that will not be entered into here. In terms of research, for the kinds of reasons elaborated at various points in this document, we believe there is a good case for fundamental as well as applied medical research in this country. That issue will not be discussed further here.Rather, the question that concerns us is what need there might be for a greater scientific input into medical research in SA. Three tentative points may be made in this regard.

Firstly, in the hightech area: while medical biochemistry in SA is strong, nevertheless there is need for a solid backing in terms of biochemistry and microbiology research in science departments, and perhaps for more communication between the two. There could for example be more joint work between science and medicine departments in terms of research on developmental biology. Similarly there could be a case for joint work on medical biophysics and biomedical engineering.

Secondly, research on the strongly interrelated areas of community health, primary health care, and nutrition has a major relation to environmental studies and ecology, and there could be considerably more interdisciplinary research on these topics involving cooperation between science departments and medical research units. There is of course a major social science component to such studies.

Thirdly, the latter research could, as in many other subjects mentioned above, have a strong component of community involvement; indeed this already happens in many community health projects. It could also include school research projects which monitor health and nutrition conditions in a local area, and focus in particular on the relations between health and nutrition in different sections of the community.

Chapter 22

Community Science

The question here is how to deploy science to the benefit of the economy and community in general, and in particular to the benefit of under-privileged areas. This is a potentially important area (cf. FRD 1992, Ellis 1993), but - with the exception of Energy, and to some extent Resource Management - little has been done so far in this country.

Among the kinds of issues of relevance are resource management together with environmental management and rehabilitation, mentioned previously, and agriculture, forestry, and nutrition, considered above. Other areas that might be developed in this spirit could be housing, transport, information, and education (however housing and transport would involve mainly technology transfer rather than scientific issues). Space precludes considering all these topics; here we consider in turn two specific and centrally important areas for community science: Energy and Water.

In each case, as in the case of environmental studies, the research involved is true interdisciplinary research involving technical issues as well as topics that are the concern of the social sciences and the realities of developmental problems (see e.g. PANOS 1987).

A key issue is how one attains a suitable enabling process of consultation between communities or their representatives on the one side, and scientists with the appropriate technical skills on the other. This is an area requiring considerable thought and careful development. Such consultations need well-thought out input from the scientific side, outlining established scientific and technical possibilities to the community members or representatives, as well as a willingness to listen carefully to the community problems and suggestions in order to creatively consider the scientific aspects of new options and possibilities.

22.1 Energy

Energy research studies the optimal provision, storage, use, and conservation of energy. This is important for both urban and rural development; it can only be properly tackled as an interdisciplinary subject.

The issue to be considered is providing increased access to affordable and convenient energy sources, particularly electricity, with appropriate environmental safeguards, and with a focus on renewable energy resources (Eberhard and Williams 1988).

While much of the technology to achieve this already exists, there are some interesting science and technology topics worthy of further study (PANOS 1990). Much research has been carried out over the past decades in the case of the modern sector of the economy; until recently it is the poor who have been left out of these studies. This has new been remedied: we are fortunate in having a very strong research initiative under way in this area (EDRC 1992).

If research becomes orientated more strongly towards addressing the needs of the poor, it is likely the research topics will straddle conventional disciplines. For example energy provision for peri-urban communities will be tied to housing, health, demography, etc. In contrast, the 'dominant' industrial economy has a high degree of functional segmentation - specialist research can more easily be linked to applied areas. But delivery of welfare to impoverished communities means giving attention to an interlocking network of scientific endeavours. It also means paying attention to the technology, implementation, and developmental aspects (see e.g. Theron 1992).

22.1.1 Electricity Distribution

There is a need for investigation of lower cost electrification distribution technologies, including more efficient and cheaper conductors, transformers, and metering. Much of this work is currently under way and is fairly applied technological research. Examples are single-wire earth return systems and the application of intelligent solid-state systems to facilitate pre-payment and demand-side energy management. It is possible that it may be worth tracking the potential of super-conductor research to achieve significant cost reductions in electricity distribution.

22.1.2 Local Energy Generation

We also need research into more reliable and cost effective off-grid electricity generation technologies for remote area applications. There has been a great deal of research over the past two decades on renewable energy technologies, including materials developments in fields such as photovoltaics. Advances continue to be made, and although such research is expensive, universities on the periphery (e.g. University of South Wales) have managed to contribute to world knowledge frontiers and have produced photovoltaic cells with record efficiencies. Most research in SA has been directed to system design - matching variable energy demands with stochastically variable natural energy sources (solar and wind). There is room for systematic modeling of hybrid systems. Other research needs are much more applied and relate to the achievement of improved standards and more reliable system components.

22.1.3 Energy Storage

The greatest obstacle to cost effective off-grid stand-alone electricity supply systems has been storage technology and a significant break-through in battery systems has not yet materialised. There is room for basic research in this area as well as other energy storage techniques.

22.1.4 Improved Combustion

In terms of large-scale central electricity generating technology, it is unlikely that South Africa can afford to build another polluting coal-fired station. A number of new technologies are on the horizon, including fluidised beds and combined cycle units. Research needs are mainly for local adaptation of internationally available technology, but this may involve scientific research on aspects of combustion of SA coals.

A particular challenge is efficient combustion of urban waste to produce electricity. In other countries entire electricity stations are run on waste; the economics and technical side need investigation in the SA context.

22.1.5 Passive Solar Buildings

Economic and Environmental pressures to achieve improved energy efficiencies and cleaner technologies present a number of challenges along the entire electricity filiere, from generation to end use. Most of these seem to be in the realm of applied technological research in fairly well understood areas of engineering science. An exception may be the field of passive solar building design, where the interactions of outdoor and indoor climate in relation to different building designs seem still to be inadequately modeled.

22.1.6 Air Pollution

One of the most serious environmental impacts of energy production and use is the contribution of hydro-carbon combustion emissions to poor outdoor and indoor air quality and consequently to respiratory diseases which are the second largest cause of infant mortality in South Africa. There is need for systematic scientific research to quantify causative relationships.

22.1.7 Acid Rain

Another environmental impact not well quantified in South Africa is the effect of acidic deposition, as the result of SOx and NOx emissions from coal combustion, on agricultural and forestry production and on the natural environment. We need to strengthen environmental impact studies associated with large energy investments.

22.1.8 Alternative Energy Sources

In the long term we need renewable energy sources which produce energy in convenient form and conveniently at the time required.

* Hydro-electricity is an ongoing option, but of limited use in SA because of our limited water resources; wind is certainly very usable (cf. the once ubiquitous windmills) but is periodic.

* Bio-energy is promising if properly managed but can place great strain on the environment (the fuel-wood crisis) and is in competition with the rest of agriculture.

* Solar-hydrogen systems seem the most promising longer term option - coastal deserts and hydrolysis of sea water.

* Fusion - extremely expensive research which requires international cooperation. We can only make a limited contribution here.

* Fuel cells for modular or decentralised systems.

* Really we need a brand new idea - something completely different [mini black holes? matter-anti matter reaction? cold fusion ??? ...]

22.1.9 Fuelwood

An energy supply option which is relevant to the poor is fuelwood and there are a host of problems and possibilities which we need to understand better. One is agroforestry - the integration of woody biomass species in small-farming systems, including questions such as species selection, and opportunities for productive interactions with crop systems. Another is the extent, rate and mechanisms of woodland denudation and environmental degradation (using remote sensing imagery, botanical ground-truthing, and agricultural and anthropological research on traditional farming systems and practices for managing natural resources). The great challenge in this field is to understand human-natural environment interactions through the combination of quantitative biological and environmental sciences with social science disciplines.

A further aspect here is the efficient use of fuelwood, once collected. An interesting example of research in this regard is the development of the Campbell CUFF (a very efficient wood-burning stove), evaluated at the Wits Rural Campus at Klaserie in the Eastern Transvaal.

22.1.10 Data Collection and Modeling

The whole enterprise of integrated energy planning is enhanced by the application of scientific method to data collection on the energy system and the modeling of demand scenarios and energy supply options. In SA, this work is in its infancy. The data collection side is another area that could become the topic of school projects.

22.1.11 Research Priorities

EPRET (The SA Energy Policy Research and Training Project) has been set up in the Energy For Development Research Centre at UCT, to consider energy policy specifically in the case of the urban and rural poor. Its work covers the following areas (EDRC 1993), reflecting a considered view on priorities in this area at present:

a) *Background*:

1: Integrated energy planning: methodology for policy analysis and research.

2: Development context for energy planning in SA.

3: Background on the SA energy system.

b) *Energy Demand Analysis*:
1: Energy demand in under-developed urban and rural areas.

c) *Rural Context*:
1: Energy and sustainable rural development.
2: Energy and small scale agriculture.
3: Energy supply options in the 'homeland' areas.
4: Energy supply options for farmworkers.
5: Rural electrification.

d) *Urban context*:
1: Energy supply options for urban households.
2: Energy for urban micro-enterprises.
3: Energy and urban mass transport.

e) *Supply side*:
1: Afforestation and woodland management.
2: The electricity distribution sector.
3: Household hydrocarbon fuels.

f) *Cross-sectoral studies*:
1: Energy efficiency and conservation.
2: Energy and environment.
3: Southern African linkages.
4: Investment requirements and financing mechanisms.
5: Household energy pricing policies.
6: Energy institutions.
7: Human resources in the energy sector.

This program is presently under way; its content show clearly the interdisciplinary nature of the research required. As mentioned above, this does not cover energy needs and supply for the modern economy; that is adequately covered by existing research groups and studies.

An important component is to train students in this kind of interdisciplinary work, with a strong base both in developmental studies and technical issues, and the relation between them. Such training is provided for example by the UCT Energy for Development Research Unit.

22.2 Water Research

Water research studies the optimal provision, storage, use, and conservation of water. This is extremely important for both urban and rural development; indeed in many respects, shortage of water is going to be the major limiting resource for the development of SA in the future, so water research is one of the most important studies we need to undertake. A crisis in this regard can be expected by the middle of the next century, and possibly much sooner. The major aim of water research is to seek methods and strategies to deal with this.

Many of the concerns are the same as those for electricity, involving supply side and demand side estimates, and issues of efficiency of use and conservation. Again it can only be properly tackled as an interdisciplinary subject, involving meteorology, geology, biology, physics, chemistry as well as economics, sociology and law.

The Water Research Commission has developed a very well thought out set of research priorities for SA. The department of water affairs has instituted a country-wide series of systems analyses on catchments, particularly those encompassing metropolitan areas (e.g. SW Cape, Vaal catchment, Mgeni/Durban). These incorporate futures research and are designed to facilitate rational management of water resources.

In the sanitation area, SA research is world class, and techniques developed here for municipal treatment have been implemented in various other countries (Ekama 1992). What is missing is a comprehensive scheme to tackle the issues for poor rural and urban communities, such as the EPRET project just described. Some steps have been taken in this direction, however: the WRC has developed draft terms of reference for a Coordinating Committee for Research on Water and Sanitation in Developing and Rural Communities (CCRUC).

22.2.1 Supply

The need is to assess the nature of and develop appropriate technology for maximal sustainable water supplies from atmospheric sources and surface and underground water resources (economics of supply and demand, optimisation of water resource systems, characterisation of flow, return flows). These involves hydrology (considered previously) as well as consideration of desalination, possible augmentation of precipitation, and effects of deforestation on microclimates.

A crucial issue is prediction of future water supplies, involving meteorology in the short term, and climatology in the long term. The issue of global atmospheric warming is of great importance here.

22.2.2 Demand and Conservation

The issue here is estimation of the demand for water in the various sectors: urban (domestic, industrial) and rural (domestic, farming). Long term estimates are required, depending crucially on prediction of future human population size through suitable population models, as well as short term estimates such as the effects of weather and economic trends on demand. A key issue is water conservation methods, and technologies for recycling water. An important area is the use of water for agricultural purposes, in particular through irrigation. A major factor here is water loss through evaporation (including transpiration), and the steps on might take to reduce evaporation.

22.2.3 Quality

This has many aspects: microbiological quality, chemical quality, physical/aesthetic, salination and other water pollution. Research on catchment areas concerns their ecology and run-off (sediments and dissolved minerals). Research on potable water concerns treatment and distribution. Health-related water quality work assesses the impact of water quality on human health, and treatment for deterioration in source water quality. The aim is to develop appropriate models for water quality management.

22.2.4 Waste Water & Sanitation Research

It is critical to consider sanitation and waste-water disposal as an integral part of water research. SA has developed advanced fresh-water treatment technology, based on bacterial systems. Major problems remain regarding industrial effluents and municipal wastewater, as well as sewage treatment for the poor. Particular topics needing attention are marine disposal of effluents, and water reclamation from sewage and industrial effluents, in the latter case the issue mainly being research into how to build an adequate base for technology transfer and implementation (most of the technology being already available).

22.2.5 Treatment of Water for the Currently Served Communities

This requires improved knowledge about mechanisms and efficiencies of treatment processes, developing guidelines for cost effective process selection, and improved knowledge of water quality changes in the distribution system.

22.2.6 Water Supply and Sanitation for Developing Communities

The issue is cost-effective provision of water to the unserved communities: developing appropriate standards and assessment procedures, assessing existing local and international technologies and systems, exploring ways to maximise the use of local entrepreneurs in the construction, operation and maintenance of water systems, developing alternative innovative systems where required, and developing drought response policies.

22.2.7 Research Policy

This is an area of utmost importance for SA. It is in respect of the last area - water supply for developing communities - that most needs to be done, through a research scheme that is analogous to EPRET. The overall issue is adequacy of total water supply in terms of quantity and quality.

A major programme should be set up, based on the EPRET model, that tackles on a comprehensive interdisciplinary basis the issue of water supply for rural and urban households and agriculture (in the urban case, smallholdings). This could be an extension of existing Water Research Commission programmes, the particular concern being to ensure that its aims and goals are sufficiently inclusive of social and economic issues.

The kinds of issues to be tackled are suggested by a National Academy of Sciences study (NAS 1973): In terms of supply, rainwater harvesting, runoff agriculture, irrigation with saline water, wells, other sources of water. In terms of water conservation: reducing evaporation from water surfaces, reducing seepage losses, reducing evaporation from soil surfaces, trickle irrigation, other innovative irrigation methods, reducing cropland percolation losses, reducing transpiration, selecting and managing crops to use water more efficiently, controlled environment agriculture, other promising water-conservation techniques. The programme must also consider the management aspects in their proper environmental and community context

(Thanh and Biswas 1990).

There is again an need for interdisciplinary training of students, giving a sound basis in developmental studies and issues arising in application of science and technology for development.

Chapter 23

Human ecology

For a variety of reasons, SA has a special opportunity to develop an effective cross-disciplinary approach to human evolutionary research. The potential is there for a much-needed, world-leading model for future endeavours. The foundation for the opportunity has been established by several internationally prominent scientists, including Broom, Dart, Robinson, Tobias and Brain. The palaeo-anthropological base established by them and other SA scientists could be integrated with research involving modern humans of differing ethnicity. Geneticists, medical practitioners, historians, philosophers, anthropologists and other experts could become involved in a common research programme of human ecology.

This should be integrated into teaching, particularly presenting the relation between the past and the future - history and futurology, to give a full and proper time dimension to the understanding of what is happening in Africa. Much is made of the spatial dimension of Africa, yet little of the temporal which is ultimately just as or more critical. One of our failings is that our view of the future is nearly always far too short, with disastrous consequences such as a lack of planning for droughts, population increases, and other hazards. An aspect of futurology is that of developing possible future scenarios and choosing those that are more desirable, as part of the process of goal-setting. Once a goal is set, one has already taken the first step towards achieving it. History should be taken back to the Pleistocene to give a proper perspective (cf. Barkow *et al*, 1992) and to help lead into habits of estimating futures on time horizons such as a decade and longer for economics, and up to 500 years or more for natural resources. Two particular issues are of importance here, apart from the overall evolutionary and historical perspective that will be gained.

23.1 Sources of Violence

Sometimes the view is put forward that war and violence are inevitable because they are part of our biology. The Seville Statement on Violence (UNESCO 1986) summarises research from animal behaviour, psychology, brain research, genetics, and other areas contradicting this view, and suggests the importance of this conclusion: "Biology does not condemn humanity to violence and war ... working together [to end war] must begin in the mind of each person with the belief that it is possible."

The issue is ultimately of major importance (even if somewhat theoretical from a practical viewpoint of confronting the violence that has been endemic in SA).

23.2 Population Growth

In the end, apart from possible problems due to major ideological/religious conflicts, the major crisis affecting humanity world-wide in the next century will be that due to human population growth (PRD 1992). The major scientific academies of the world met in Delhi in October 1993 to discuss the role that scientific research can play in understanding the nature and effects of this population growth. Papers were presented on demography, the relation between population growth and resources, the role of women, etc. The intention is to place before the governments and non-governmental organisations of the world an agreed statement on population growth, its relation to the environment, and the possibilities for its reduction.

The issue is equally important locally. There is a continuing need for long range population projections (giving low and high estimates of the likely future), together with use of these estimates to determine the resource and other implications for the future of SA, and to research and recommend strategies to deal with the issue.

The population estimates are under way as needed. In terms of studying impacts in an integrated way, some work has been done on this already (Baker 1976, RSSA 1978). There is a need to continue research on this topic on an ongoing basis, for this is one crisis that will face us for certain. Almost all the other long term crises that will confront us (such as the critical water shortage and massive urbanisation and job-creation problems) will essentially be consequences of this one.

Chapter 24

Human Development

Two particular aspects of human development have a strong relation to science: Science Education, and Science Philosophy together with its relation to culture.

24.1 Science Education

The importance of science education cannot be overstressed, for it is the foundation on which all else discussed here rests.

The AS&TS, JCSS, and SAVI (AS&TS 1993) have jointly undertaken an investigation of issues related to education policy for technology and raised a series of issues of importance as regards organisation: they highlight the need for a National Educational Forum, and a series of policy issues concerning school and tertiary education. These issues are considered again in Part III.

Here we are concerned with research issues of importance for science education, and turn to those after one observation: No science policy at all is possible without sound educational standards being established through schools, technikons, and universities. Excellence in teaching is a *sine qua non.* We must therefore give greater recognition to teaching and its associated scholarship at all levels, including university.

24.1.1 Science Education Research

There is a major need for research into Science and Technology Education. A start has been made in this country, as evidenced by the recently formed SARMSE (SA Society for Research into Maths and Science Education), but much more should be done.

The need is to provide, as far as possible, sound knowledge on which to base teaching methods: a questioning and testing of presuppositions about the effectiveness of lectures, laboratory work, and tutorials. Research in this area investigates errors and misconceptions that abound, the difference between expert and novice approaches to structuring knowledge and solving problems, the effectiveness of different teaching methods and learning environments, and ways of improving learning (Grayson 1992), for example through implementation of group learning methods (Pastoll 1992). Fundamental to all this is the nature of learning and the learning process.

Thus as well as knowledge of the subject matter, this work involves educational psychology, cognitive science and role it can play in understanding learning, and the understanding of group processes and educational methods. It must aim at the most effective use of scarce resources (it is no use suggesting teaching methods that require intensive contact time with lecturers or teachers, when that time will not be available). Thus it inevitably also carries over into areas of resource management. All of this is true for education from the pre-primary to the tertiary level. Thus there is a need for research into science education at every tertiary level institute concerned with teaching science, with some selected institutions chosen to house centres of specialisation in this area, acting as resource centres for all the others. This activity should feed into and be informed by science education research into school level science teaching, based in faculties of education and teaching colleges.

A particular problem is Applied Science education and the best methods to accomplish this: how much should be taught in classes, tutorials, etc., and how much 'on the job'.

There are two particular areas that deserve special attention.

24.1.2 The School Maths & Sciences Syllabus

One can make a case that apart from all the other problems besetting our school system, the school syllabus - and in particular the associated examination system - is a major stumbling block in science and maths education.

Thus an important need is research into best syllabus choice and examination methods from pre-primary to secondary school levels. This should emphasize building useful skills and attaining understanding, rather than rote learning; an example of the kind of development in mind (in the case of school mathematics) is given in Ellis (1993c). Development of such a new syllabus should be undertaken as a research programme in which the ideas are first thoroughly tested in pilot projects in chosen schools, based on resources centres serving a cluster of schools. Development of appropriate assessment techniques is a crucial issue.

24.1.3 Public Understanding

It has been emphasized above (Section 4.7 of Part I) that public understanding of science is an important issue, in particular because of the need for an environmentally literate population. Thus there is a need for innovative systems for mass education that spread a wide understanding of the nature of scientific investigation, of cause and effect, and of research and discovery, through programmes such as those sponsored by COPUS, the UK Committee on the Public Understanding of Science (COPUS 1992).

A particular need before such a system can become effective is to research the state of public knowledge of science: this is a helpful diagnostic tool, underlying success of all work aimed at increasing this understanding. Almost nothing has been done in this area in SA.

When such programmes have been initiated, again research is needed to see how successful they have been, linking this work in to the science research activity described in the previous paragraph.

24.1.4 Public and School Participation

A theme that has emerged in many cases in the sectoral studies above, is that an important way to contribute to research and also teach the public about science is to devise research projects where public can - after some initial training - take part.

A particular example is the S A Bird Atlas project (Harrison 1992). This Atlas of SA Birds demonstrates the potential of the reservoir of amateur expertise to gather important scientific data. Information gathered through the project relates to ecology, migration, seasonality, monitoring, biogeography, and conservation; apart from its academic interest, its importance derives from the fact that birds are a sensitive environmental indicator.

Similarly, bird ringing, fish tagging, and the Protea Atlas projects (Rebelo 1991) help keeping a basic inventory of our natural resources. This kind of work can research ecological or environmental conditions, for example investigating range deterioration (Parker 1974).

Thus one can use research programmes as methods of training the public in scientific methods. We suggest each sector should consider the way that such projects could be encouraged in their area, emphasizing that we are not talking here of projects simply for the sake of education, but projects that make a real contribution to a significant research programme through their data gathering, offering an opportunity to participate in such a programme to members of the public. This provides considerable motivation, opportunities for understanding the scientific method of precise observation, and a detailed knowledge of some particular area of science. It is a very powerful form of scientific education.

The further point then, is that such programmes can deliberately aim to set up school science projects in a coordinated country-wide way. This would involve training for both pupils and teachers in the concepts and methods used in that particular study, and regular quality checks on the data being provided; the data would be rejected if below quality, so acceptance of the data would be the first goal to aim for.

Each school participating would get some kind of apparent benefit from so doing, apart from the satisfaction of taking part in real research. This would be partly financial (at least some financial support being given for the research undertaken), partly recognition through having their work acknowledged in regularly published reports on the results obtained, and partly scientific in terms of being given such reports and summaries as they are prepared. There could also be prizes for the best school units taking part in such projects.

An example of such a scheme is a USA nationwide experiment to find out which seeds garden birds like best (*New Scientist*: 23 October 1993, p.9). This is part of the National Science Foundation's informal science education programme. A local example is the Schools Water Analysis Project established in 1992 in the Faculty of Education in Stellenbosch (see *On Stream*, Summer 1994).

Thus we very strongly recommend setting up a national programme to promote, initiate, and support such projects in schools. Some suitable topics have been mentioned above; particular opportunities are,

- weather observations,
- water monitoring,
- soil monitoring,
- environmental monitoring.
- resource monitoring.
- census data,
- community health.

The last two are particularly interesting in that we currently spend large sums of money on getting such data, but this is either very spotty (isolated surveys) or very spasmodic (a census taking once in ten years). Census data-taking as an ongoing school project offers the possibility of having much of the census data required (family and house sizes, migration data, agricultural production, and so on) on an ongoing, up-to-date basis, while at the same time providing school children with experience in elementary social science methods. To those querying the practicality of this, it is worth pointing out that school children have been used for such data-gathering in a survey of Friemersheim (van Heerden 1986). Certainly large-scale organisation offers a host of new challenges, but these should be surmountable if the aim is to build up the required capacity over a period of time.

A similar possibility arises in community health: in this case such projects would monitor health and nutrition conditions in a local area. When sufficient such projects were running in a particular area, they could be integrated into an overall environmental and resource evaluation system for that area.

24.2 Science Philosophy & Culture

The impact of science on philosophy and on public understanding of the nature of reality has been enormous. However there have often been overstatements or misunderstandings of the scope and implications of science - even among scientists. This is partly because most scientists do not regard the history and philosophy of science as an interesting field.

There is a recent resurgence of interest in these areas, partly driven by rising dissatisfaction with the role that science has played in society, and partly by the dramatic new discoveries at the boundaries of physics and astronomy, each embodied in various recent popular books that have attained a wide readership.

At a superficial glance, these studies are highly esoteric and useless. However they in fact are a very important in terms of shaping the way we view the universe and ourselves - for they touch on the issues of our origins and existence. Indeed one of the prime issues is what, if anything, science has to say on the meaning of life. These studies draw on the results of astronomy and cosmology in their research on the origin of the universe, of elementary particle physics in its search for a unified view of the foundations of nature, and of human ecology in its research on the nature and origins of humanity.

It is suggested that a small but powerful research programme should be run on these issues. Some of the issues arising are outlined in Ellis (1993b).

24.2.1 Ethical Issues in Science and Technology

A related area of considerable contention and importance is that of the ethical issues arising in science and technology (Barbour 1993). It has been emphasized in the section on environmental sciences that particular ethical views inevitably underlie all our management decisions; this ethical basis should therefore be subject to particular scrutiny and debate.

The nature of the decisions to be taken needs to be clarified by suitable research. Apart from environmental issues, particular topics of importance relate to nuclear and other weapons research (excluded from this paper);

* ethics in medical and animal research;

* ethics in biotechnology and cloning.

The topicality of these issues – see e.g. MRC (1993) for a position statement on the case of medical ethics – makes it clear that a small but powerful research unit should be instituted to look at them. Its conclusions should be used to help set limits on what research is regarded as permissible.

Chapter 25

Brain and cognition

In looking at the current 'Hot Topics' in world science, apart form genetics and developmental biology, one of the most exciting and promising is research on the human brain and cognition.

This area is just at its beginning, but has promises of leading to the most exciting discoveries of the next century. It involves a host of topics: neurology, psychology, physiology, molecular biology, biophysics and biochemistry (including use of Positron Emission Tomography cameras), psychology, computer science (including particularly 'artificial intelligence' and neural nets), philosophy, ethology and evolutionary theory. It starts off being purely 'blue skies' research; but insofar as it succeeds in its aims of understanding the functioning of the brain and cognition, it has the potential of revolutionising medicine and technology, in particular information technology, in ways as yet undreamt of.

To make progress demands interdisciplinary teams with truly creative minds. They could be large or small. We have no particularly outstanding expertise in this area in this country, but there is nothing to stop us setting up such teams - at comparatively little expense - if we so desire.

We suggest investing a relatively small amount of money in setting up one or two small but excellent teams to work in this area, so keeping a foothold for us in one of the most exciting and significant areas of research for the future.

Chapter 26

Science Policy Research

Finally, Science Policy is - as is clear from all the above - a complex subject; this document only touches the surface of a detailed science policy that is needed in each area.

Now the major decisions about science policy will be made by various official bodies, but in taking those decisions they will need properly informed research on science policy, such as that provided by the Science Policy Research Unit at Sussex University (SPRU 1992).

Such research is needed,

a) In relation to *science and technology* (S&T):

*their inter-relation and effect on the economy.

This is an important topic that should be studied by an appropriate research unit.

This should be run in conjunction with a greater effort in research into

* principles of resource and environmental management, in particular development of resource economics,

which at present is a crucial gap in our expertise.

b) In relation to *science proper* (as discussed in this document): developing in more detail the themes discussed here. Topics arising are

* evaluation of research quality and impact,

* criteria for choice of projects, and

* the choice of overall strategic thrusts, together with consideration on how best to implement them.

We advocate small but good quality research units to cover each of these themes.

Of course we then face the obvious recursive theme: who checks the quality of the research on science policy by the science policy research units? Do we need science-policy-research policy research units? We leave this as an open question.

Part III

SUPPORT AND PRIORITIES

Chapter 27

Support for Research

Given the needs for research as discussed above, there is a strong case for the overall level of scientific research being kept at least at the same levels as at present (in real terms), but with some changes in priorities and rationalisation of effort.

In fact one can suggest that investment in research in science should be increased a great deal, by redirecting some of the vast amount of research moneys previously used in wasteful areas where huge sums were used in supporting the apartheid vision, for example the defence and atomic energy industries, to the kinds of areas discussed in this document. This would allow increasing research expenditure in all the priority areas identified and easily attaining the overall research programme envisaged here.

Whether or not that re-allocation is achieved, when the economic situation improves the investment in scientific research should be substantially increased, as it is (together with education) the ultimate source of future welfare for SA.

The level of technological research should also be greatly increased, particularly in industry, but that is outside the scope of the present document.

27.1 Organisation

Organisational issues are discussed in the following section. For the moment the comment is simply that there is a need for quasi-permanent committees with a clear mandate to review the really pressing scientific issues in

SA plus the long term needs. They should in particular tackle issues of interdisciplinary cooperation in applications of science, and develop interdisciplinary areas of research including science education. The work of these committees must receive the widest publicity together with its memoranda and decisions.

27.1.1 Rationalisation

A significant task of these committees is to look at the rationalisation that may be possible in each area, in order to make the best use of our scarce resources. An example that has been mentioned above is geology, but the issue occurs in each subject.

27.2 Books and Journals

A specific and urgent need is to ensure the continued supply of scientific literature to this country. Rising costs have already resulted in cut-backs and made access to current literature more difficult. There are two concerns: to keep up-to-date and relevant the already existing good collections in various centres, which have begun to lag in terms of modern journals and books; and to build up good modern collections in particular areas at selected centres as part of a rationalisation exercise aimed at correcting historical imbalances.

A task force should consider this issue in detail, in particular examining

a) obtaining increased funding for this vital area,

b) what kinds of pressure could be exerted to remove taxation on books and journals that underlie scientific development,

c) what kind of organisation could make the latest books and journals in each research area available in this country at selected research centres, with reasonable access guaranteed to all parties carrying out significant research work in that area (e.g. through centres dedicated to maintaining a current stock of journal and books in each particular research area). This theme needs to be developed in detail in each subject area.

27.3 International Communication

It has been emphasized there is a need for international communication, both overseas and within Africa. The Science Councils have all already taken a number of initiatives here: all have formal programmes for international cooperation, and strategies for involvement in Africa.

27.3.1 International Collaboration

The need for apolitical science liaison and collaboration with other countries, enabling good linkages to the international S&T community, should also be reflected in the organisational structures developed. However it is suggested there should be a minimum of bureaucratic effort devoted specifically to this purpose; rather the institutions already mentioned (the Academy, Research Councils, and specialised Societies) should each be encouraged to set up links with the corresponding international bodies and organisations in other countries, and in particular in other African states. The implication is that funding allowance needs to be made specifically for this activity.

This has already started to a limited extent. For example, through the FRD we already have membership of ICSU (the International Council for Scientific Unions), for example IUPAP (the International Union of Pure and Applied Physics, see IUPAP 1993), and various specific memberships of ICSU councils have been reported in the body of this document. More locally, Prof J A Thomson (UCT) took part in the first meeting of the African Academy of Science's Policy Advisory Committee for Research Priorities for the Education of Girls and Women in Africa, held in Nairobi in 1993.

27.3.2 Visitors and Trips Abroad

This involves funding of visitors to SA, and of SA research workers to go abroad for research collaboration and to attend meetings and conferences. Funding is also needed for representation on international committees.

Particular effort should be put into developing continent-wide research collaboration, initiating or joining multi-national research councils in Southern Africa, especially in connection with shared resources such as fresh water. Associated transport and subsistence costs should be funded as a significant part of our increasing contact with the rest of Africa.

27.3.3 Electronic Mail

It is important to retain the good electronic mail facilities that we have at present, so as to facilitate international contacts and collaborations. Currently our situation in this regard is adequate, and is a great assistance to science in this country.

27.4 Equipment

Basic equipment is needed across the board, with specific needs in each subject and a general need for computers of adequate power. We are reasonably well supplied in this regard at present.

The more costly items needed have been mentioned in the topic discussions above: advanced electron microscopes, X-ray diffraction equipment, nuclear magnetic resonance equipment, telescopes, research ships for studying the marine environment, and so on. Part of the process of rationalisation is to come up with a plan that ensures we are up to date with this kind of equipment at a reasonable level. In some cases the solution will be to use overseas equipment rather than buy our own; this needs to be looked at carefully in each case.

In each case we need clarity on what facilities (equipment, computers) are needed, and what kind of organisation could make the latest technology in the area available in this country with reasonable access guaranteed to all parties carrying out significant research work in the area (e.g. through centres dedicated to particular equipment and research areas).

27.4.1 Shared Facilities

For expensive equipment, planned sharing is vital. Coupled with this is the need for travel funds to enable that sharing to continue and expand, as well as the cultivation of a philosophy of sharing and collaboration. The issue is how to share the costs of major equipment of this kind so that all who can benefit have access to them. This can be done by siting them at particular research groups of expertise, who operate them, and on an agreed basis let other groups use them (the SAAO being a good example of this kind of situation). A plan of rationalisation needs to consider this carefully: how many of each expensive item do we need, where should they be sited, and what cooperative arrangements can be made for sharing them. Funding should go to preferentially groups who make good proposals for cooperation and integrated research programmes.

27.4.2 Maintenance and Repair

It is essential that the equipment plan allows for maintenance and repair of all the equipment envisaged. This requires technicians of adequate calibre, plus the needed spare parts.

This is an area where local enterprise can sometimes provide an appropriate local answer at a fraction of the price of imported products. For example a former MSc student in microbiology has set up a manufacturing company for small to medium sized molecular biology equipment - things like electrophoresis apparatus, DNA sequencing apparatus, power packs, vacuum driers, etc. These are cheap relative to imported equipment, and he often designs equipment around local requirements. He now sells throughout southern Africa. These sort of entrepreneurial enterprises should be positively encouraged.

27.4.3 Supplies

Equally important is to ensure adequate specialised supplies are available: pure chemicals, radio-isotopes, biological materials, liquid nitrogen, and so on. A rationalisation plan needs to look at this too, in particular what we can reasonably produce here and what should be imported.

Again we need to encourage local entrepreneurs to take an initiative here, for example we need to establish local companies to manufacture enzymes and other reagents.

27.4.4 Satellite Imaging & Remote Sensing

A need common to many programmes is access to up to date satellite imaging and remote sensing data. This need is common to ecology, oceanography and meteorology, environmental and geological sciences, urban and regional planning, and as a base for resource use strategies. The best way of accessing such data needs careful investigation.

This is also of concern to all countries in Sub-Saharan Africa (Falloux 1989), and could possibly be the subject of joint agreements.

27.5 Major Projects

From a purely scientific viewpoint, there is little to be said for Atomic Energy Board research, in particular uranium enrichment, and the research work at Armscor and its offshoots. Their commercial and technological value is a separate issue, outside the scope of this document. It may well have sound value in those terms, but it needs very careful scrutiny, as the whole scientific research budget is very small compared to expenditure on these kinds of projects. Ideally a substantial fraction of that money should be re-channeled into scientific projects of the kinds described in this document. This would easily allow continuation of all our 'big science' projects (as well as expansion of the FRD core programme and initiation of new major projects).

These projects - NAC, SAAO, HARTRAO, and the Antarctic base SANAE - are used by a wide variety of scientists from different parts of the country; SAAO is an international facility with widely recognised scientific value. They each make a positive contribution to SA science.

a) *SAAO* and *HARTRAO* are good value scientifically. There is a strong case for a new telescope at Sutherland, if some of the cost can be shared with other countries through international collaboration.

b) *NAC* is controversial, as discussed above. Rationalisation is needed here, hopefully reducing costs of the cyclotron by various measures, and using the funds thereby released towards a major solid state physics and materials science programme. The van de Graaff accelerator and a nuclear physics programme should be continued.

c) *SANAE* is expensive for the scientific value of what is achieved, but nevertheless does play a useful role in major international research programmes of significance. It also has diplomatic and political significance which probably raises its value to the country above that as a purely scientific enterprise. Thus there is a case for its maintenance (and the supply ship that is a major cost) as a base for scientific research programmes, provided the basic funds for maintaining the base - as at present - come from sources other than the FRD.

d) A *Supercomputer Centre* could be a good major project to embark on in the near future, as it would provide a base for many computational activities of importance. It would not be that expensive, and would provide a good base for training of students in modern technology.

27.6 People

Above all, scientific research depends on attracting and keeping people with initiative and ability. This is the reason for the importance of science education and of the public image of science.

Good quality training must be available for those who want to go into the sciences - they must be able to make good their intentions, through preparation at school and then training at tertiary institutions from the undergraduate to the research level. We are in a reasonable position in this regard in this country, at the historically white universities; the problem is to bring the historically black universities up to the same quality without losing what we have in the existing good quality programmes.

Having been attracted into science, good researchers need to be supported adequately - but not outrageously - in their scientific research. Thus we applaud the FRD emphasis on supporting people in science at all levels (see *Winning People*, FRD 1993).

This also means we have to be concerned about the brain drain from SA, and consider ways of counteracting it. Providing a good research environment and support, combined with good graduate teaching facilities, is the prime way we can do this.

27.6.1 Inclusivity

There is an urgent need to attract ALL sectors of the South African community into scientific careers, so that it is not perceived as a 'Whites only' hangover of the Apartheid era. It seems probable that the lack of Black recruits is firstly because of the poor science teaching and facilities at most schools, and second because it is perceived as a poorly paid, government sector career.

These aspects must be redressed through programmes tackling the issue of school science on the one hand (see below), and improving the image of science, in particular giving knowledge of the abilities and opportunities it provides, on the other.

The FRD, MRC and ARC are all involved in the activities discussed in this section, and have large investments in these areas.

Chapter 28

Organisation

Broad goals for a science policy of the future are suggested above. In order to be implemented, they would have to be debated in some suitable consultative process, in competition with other proposals that might be put forward, and some suitably modified version agreed on. Given such agreement, various organisational issues would then arise, for example, by what mechanism should we establish priorities and allocate funds? The IDRC (1993) have looked at organisational issues in some depth, and come up with the following series of topics relating to Science and Technology (S&T) policy:

1. Decision making and resource allocation,

2. Focusing on the problems of the majority,

3. S&T roles of higher education,

4. Science, technology, and international competitiveness,

5. Linkages to the international S&T community.

There is not room here to discuss the organisational issues in any depth. They have been addressed elsewhere (e.g. ANC 1990, FRD 1991, 1992, *Africa 2001* 1992, IDRC 1993, Whiston 1993); the aim here is simply to outline some suggested overall attitudes to them. Organisational needs arise in relation to each of the major themes identified in the previous sections.

28.1 Priorities and Funding

The issue here is the mechanisms for establishing broad science policy, setting priorities, and deciding on resource allocation, including determining the nature of funding channels and the method of making specific policy decisions.

There is a need, as discussed above, for a substantial re-orientation of science and technology research so that it is more responsive to community needs, and more effectively supports social and economic goals. To enable this, ideally there should be a system which allows ongoing consultation between community members, those formulating economic and social policy, and those working in science and its particular sectors (e.g. energy), to ensure that science and technology research contributes effectively to the achievement of local and national goals. However this process must also encourage some longer term strategic research - which is less tied to immediate social and economic objectives; in other words, more basic research which is formulated with foresight of areas where significant scientific and technological advances are possible.

Thus suitable councils or committees are needed to decide, after a process of consultation, on the principles for selection, and then to take decisions on the funding of research on a priority basis. These committees should proceed on the basis of guidelines something like those discussed in Chapter 3. They should be based on

* potential value of the proposed research to SA and its people,

* application potential of research results,

* need for increased knowledge in the field to be addressed,

* scientific merit and innovation,

* building on existing strengths,

* the chance of successful research execution.

However they should also specifically consider research gaps and strategic needs, and take steps to fill unmet research needs. In particular they should concern themselves with the following:

28.1.1 Science, Technology, & International Competitiveness

Establishment of the institutional framework for a viable R&D base for selecting, adapting, and developing applied science and new technology, particularly relating to materials processing and information-based manufacturing enterprises. This should selectively support those areas of the applied sciences that are important at present or are likely to become essential for national development in the future, encouraging and supporting increased university-industry cooperation as well as greater research efforts in industry.

28.1.2 Focusing on the Problems of the Majority

Establishment of the institutional framework to enable application of science to everyday problems through a two-way process of consultation on the nature of problems encountered and the possibility of technology helping solve them .

Given the shortage of skilled research workers in this area, it makes sense to concentrate resources in a few multi-disciplinary research centres which focus on special problem areas. Such funding can lead to the growth of research leadership and the progressive deepening of knowledge and understanding. It is possible to develop an effective continuum from more basic enquiry and modeling to more applied research, as in the Energy For Development Research Centre at UCT, where it has also been possible to foster an effective collaboration between the different disciplines of engineering, mathematical sciences, economics, and sociology. Science policy should seek to promote research in the sorts of areas identified in this document as significant interdisciplinary research themes (cf. Chapters 21 and 22), by locating potential research leaders in these areas and growing centres of excellence. Funding from national bodies such as the FRD is essential because the multi-disciplinary nature of such centres and their research orientation means they are seldom integrated into standard academic departments or established university budgets.

28.1.3 Science for Science's Sake

Continuation of institutions supporting a small but significant core of research regarded as a cultural activity, valued in its own right, independent of possible applications in society.

Specific institutional structures, something like the present Research Councils (cf. IDRC 1993) but with a greater consultative component and some change in their Boards to make them more reflective of the populations served, should be put in place for each these purposes. An important issue here is assessment of the quality of research, which can be approached in a multi-dimensional way (Thulstrup 1993). The primary method of steering of research should be through funding on the basis of the agreed guidelines, but particularly recognising the various incentives that are important in encouraging scientific research (Thulstrup 1993).

28.2 Relating to the Government

There is a need for a clear focus of high level responsibility for decision making on S&T issues, ensuring that S&T policies are fully integrated with other principal policy directions of the government (IDRC 1993). The Councils mentioned above would carry primary responsibility for S&T issues, being delegated with this responsibility by the Government, but they need to be supplemented by direct channels for communication with the Government and Cabinet on scientific and technical issues. This arises in two regards.

28.2.1 Lobbying Government on Behalf of Science and Technology

There will be fierce competition for limited resources; it is essential that the S&T needs do not get lost in this competition. Thus there is a need for cabinet-level lobbying on behalf of science and technology, preferably through a Minister of Science and Technology. He/she should be supported administratively by a small but efficient Department of Science and Technology, and in policy terms by a well-qualified National Science and Technology Advisory Committee or Forum that in turn will liaise with other organisations in the country concerned with these areas, in particular the Councils mentioned in the previous paragraph. This would also be the route by which those concerned with science and technology would help shape government decisions and policy relating to S&T.

28.2.2 Scientific Advice to Government

This is the converse of the previous: the question of the channels by which scientific advice on general policy matters, for example resource use and environmental issues, will be given to the Government (and the public).

Again there is need for cabinet-level access to give advice on matters where science can throw an important light (for example, the issue of population growth and its implications for the future).

This is a separate role than that considered in the previous paragraph; it could possibly be carried out through the same institutional channels, however to clarify its separate nature perhaps it should rather involve different people, e.g. a Presidential Policy Issues (Scientific) Advisor, again supported by a Policy Issues (Scientific) Committee or Forum, and empowered to set up policy analysis groups able to carry out scientific analysis of relevant issues. However it is done, there should be mechanisms for involvement of scientists in national planning issues.

28.3 Organisations Within Science Itself

There are already a variety of specific subject interest groups (the Institute of Physics, Chemical Society, and so on) and umbrella organisations (in particular JCSS, AS&TS). Nevertheless one can suggest there is need for greater networking of the scientific communities in the following ways.

28.3.1 Formation of an Academy of Science

There is a need (apart from the umbrella organisations) for an Academy of Science to represent the interests of science as a whole, rather than those of the various sections of science. This should be comprised of scientists and scientific administrators with established track records, able to give expert opinion on scientific issues from the viewpoint of scientists. This then can provide an important input to the Government committees mentioned above, which will represent other interests as well as those of scientists and science. The Academy could when necessary set up expert working groups to look at particular policy issues as they came up.

The Academy could also play an important role in terms of international contact. It could advise on matters relating to participation in international programmes and be the contact with the Royal Society (London), National Academy of Sciences (Washington), African Academy of Sciences (Nairobi), and so on. As is clear in this document, international environmental and other scientific programmes can play an important role in our future.

28.3.2 Research Coordination

The lack of a coordinated research attacking strategic problems in many important areas reflects a lack of real commitment among the scientific community to appropriate interaction and cooperation. This has resulted in a lack of committees in specific subject areas, developing strategic research plans based on needs and priorities, evaluating progress made, and formulating proposals for further research and applied development.

Within each broad applied subject area such committees would be very useful, providing the means for setting up and supporting the kind of interdisciplinary webs mentioned elsewhere in this document. This would probably be the best basis for inter- disciplinary and inter-subject research facilitation, implemented through a well-managed coordination operation in specific subject areas run by skilled, professional research coordinators and facilitators. The old CSIR/FRD SANCOR programme was a good example of successful coordination, but this unfortunately all but disappeared with the restructuring of the CSIR and FRD. Such structures should be revived, and similar ones set up specifically to provide links between industry, universities, and technikons. An example is the reconstituted SANCOR, now in the form of a South African Network for Coastal and Oceanic Research (SANCOR 1993).

Where research projects of an applied nature are funded, each project should have a steering committee, with representation by specialists and interested organisations. These would act as links to the funding agencies and to similar research projects elsewhere.

28.4 Science Education

A critical issue in S&T development is the quality and quantity of science education at both the school and tertiary levels. The inadequacy of school science and mathematics at present is probably the primary constraint on future scientific and technical development. A specific Science and Technology Education Forum should be set up to deal with all facets of this issue (AS&TS 1993), in particular setting the aims, strategies, and obtaining the resources needed in the production of a corps of well-trained indigenous technological manpower. This Forum should have Cabinet-level representation to ensure adequate resources are made available for this area, absolutely critical in terms of the future economic welfare of the country. It is through effective action in this sphere that we can address the racial and gender bias presently inherited by the scientific community.

Decision of allocation of resources to schools will be difficult. Two organisational methods can hope to help here. Firstly, one can create School Resource Centres in urban locations, to be shared between six or seven schools in the vicinity; then such centres can be reasonably well-equipped with audio-visual aids, computers, libraries, and so on, enabling such equipment to be well-used to benefit many students. Secondly, one can arrange a system whereby each school is encouraged to excel in some particular topic or topics. Then resources can be directed efficiently by concentrating on providing each school that equipment needed to make it excellent in its chosen area (music, drama, English, maths, etc.), while still giving a reasonable level of support in other areas. Equipment Committees, charged with optimal resource allocation for educational purposes, would give incentives to schools taking part in one or other of these schemes (financing would be easier to obtain if it was asked for in such a framework).

On the resource side, apart from mandating spending committees to ensure adequate supplies of equipment needed for science teaching in general (where possible of local origin), and sufficient textbooks of quality in particular, an important issue is to give adequate recognition and incentives to school science teachers. A possible strategy would be differential salaries, offering higher pay to teachers in this area because of its strategic importance. The relevant committees should be empowered to consider such strategies. They would also consider ways to utilise the brighter pupils as tutors to the others, giving a large multiplier effect for teaching effort, and enhancing the educational benefit greatly to the children selected as tutors.

The further issue that needs specific attention is the subject matter and the way it is taught. Specific action groups should be set up to tackle the major important areas:

* Research into learning and teaching,

* The nature of the syllabus and examinations,

* Teacher training and upgrading,

the latter depending on decisions in relation to the first two topics. Issues of quantity and quality arise; these are essential items for the Science Education Forum to consider.

A primary need here is to reexamine the school maths syllabus (Ellis 1993), which is a lynchpin for the whole of science education, but the other areas are equally needing of attention. For example there is a need to address biology teaching at schools, with respect to the development of a sensible school curriculum which emphasizes the integral nature of the physical and life sciences and the way one can explain the workings of living organisms in terms of physics and chemistry. It should also show how the concept of evolution has become a central theme in the modern understanding of biology.

At the Tertiary level, Academic Support methods and research into learning and teaching (at this level) are vital for the foreseeable future. The need here is to ensure that adequate resources are available at Universities and Technikons for these activities, and that teaching excellence and research is rewarded adequately. There is a particular need to consider ways of increasing the science and technology enrollment both at Universities and at Technikons. The 'Hidden Crisis' of post-secondary S&T education (Cooper 1993) must be urgently addressed. There is also a considerable need for adult education programmes that tackle scientific subjects and in particular mathematics, both in terms of providing technical training, and more generally for broad educational purposes.

Finally it is essential to realise that probably the most important contribution of all from the universities is in the training aspects of research: the results of university research activities should not be measured on their commercial success but on the quality and relevance of the research training they provide (Thulstrup 1993). The FRD kind of programme seems very successful in this regard, and there is a good case for its continuation.

28.5 Relations with the Public

The importance of good relations of the scientific community with the public, and of public understanding of science, has been emphasized above. There is therefore a need for specialised committees to have as their brief future work to increase the public understanding of science. An example is COPUS (Committee on Public Understanding of Science) in the UK, a joint project of the Royal Society and other groups. Their task is to support and initiate mechanisms for increasing public awareness and support of science, and to spread a scientific culture in the country (see COPUS 1992). They would need to have good liaison with public media, particularly radio and TV, and with museums. This links over into the whole area of adult education, which is important enough to have its own task force within the National Education Forum.

The kinds of task undertaken would be like that of COPUS (Copus 1992) :

a) *For scientists*:
* Media fellowships and media training courses,
* Awards for promoting public understanding of science,
* Awarding research fellowships to scientists to allow them to spend time promoting their subject to a wider audience.

b) *Directed towards the general public*:
* Prizes for books that popularise science,
* Broadening scientific coverage in broadcasting,
* Science and women programme,
* Science in museums programme,
* Media review group,
* Grants for supporting public understanding of science,
* Appointing fellows to work with the Parliamentary Office of Science and Technology,
* Lunchtime science seminars for senior civil servants from all departments.

c) *General activities*:
* Running an annual science festival,
* Setting up a data base of high quality speakers able to address general audiences on scientific topics.

A similar range of activities should be initiated in SA. To make this happen,

1) an assured source of funding needs to be established for these activities, presumably through the science budget;

2) scientists themselves must take the lead in starting relevant initiatives,

and, realising that this cannot be handled adequately simply as a spare-time activity of busy scientists,

3) people should be employed full-time for the specific purpose of popularising science.

The FRD has made a good start in this direction, for example through FRD Lecture Days and through publishing *Scientech*, but much more is needed.

Chapter 29

The Way Ahead

A fairly clear picture emerges from this survey, suggesting the kind of research work that can usefully be done in this country, both of a pure and an applied nature. In particular, it highlights – in a preliminary way – what fields are necessary for economic, developmental, or environmental reasons; and what can particularly advantageously be done here as opposed to elsewhere.

The overall concerns are to ensure a research base that on the one hand promotes optimal resource usage towards solving our problems, and on the other promotes education and understanding, both directly in terms of science and technology issues, and also in terms of broader issues, insofar as science impacts on them.

29.1 Interconnectedness of Research

The first point that emerges is *the interconnectedness of research.* The various areas merge into and support each other.

Thus the first need is for broad research support across all the areas discussed; for if any one were to be missing, it would affect others and ultimately result in a loss of quality in the whole edifice.

This does not mean that all subjects are of equal weight, but rather that research policy should ensure support of each major area to an adequate degree. There are however specific advantageous or important areas that should be preferentially pursued, for a number of different reasons.

29.2 Research Themes and Priorities

We consider in turn, subjects with clear applicability; subjects with particular suitability; basic support subjects.

29.2.1 Subjects with Clear Applicability

There are a number of subjects particularly suited to applied research. There is nothing local about this: the recommendation accords with world-wide experience (cf. Part I).

a) *Critical Technologies.*
First, there are the *'old' technologies* that have a scientific base: Metals and Materials (mining and beneficiation), Chemicals (light and heavy), Fermentation Microbiology, Agriculture and Forestry, Fishing, Mining, to some extent Manufacturing.

In each case there is need for scientific support and assistance in developing new approaches and methods, and improving old ones. The issue is to support the basic underlying sciences (see 29.2.4), and then create the channels that let science engage meaningfully with these technologies. This has been done particularly successfully in the case of fishing and mining; in each of the other areas the links between university and industry need strengthening.

There are some critical areas here that are underdeveloped in this country (in scientific terms):

* Forestry and Agroforestry,

* Soils viewed holistically,

* Ecology of Farms.

These should be the subject of special research effort, while the existing excellent research effort in Marine Ecosystems should be continued as the basis for sound fishing policy.

Second, there are the *new technologies*, where the industry is essentially knowledge based, and cannot be entered into without the required scientific expertise:

* New Materials,

* Biotechnology using Molecular Biology,

* Informatics.

The last, based on modern computer and information technology, has the potential to transform all the other technologies (old and new), as well as manufacturing, commerce, and many aspects of government. The issue here again is developing efficient use of the technology, with a strong focus on research into usability.

We should put special developmental effort into each of these areas; if we do not do so, we will languish not only behind Asia but also Latin America.

b) *Developmentally vital areas.*
The environment is a critical element in development, so all the issues raised in Environmental Studies are important, in turn relying on Physics, Chemistry, Geology, Hydrology, Ecology. There is a particular need for

* Environmental Studies of Township and Rural ('homeland') areas, including Ecological research, as a basis for reconstruction policy.

This leads on to consideration of resources, where we lack

* Integrated Resource Studies on a regional and national basis, related to developmental policy.

Also it is possible that in the future 'ecotourism' could be a major source of income for South Africa, and it is important that we don't kill the goose that lays the golden egg; it must be properly managed and based on sound scientific advice if it is to be sustainable. Thus we need

* research into proper Management of Environmentally Sustainable Tourism – in particular Ecotourism– which is based on preserving our national environmental resources.

Weather and climate is a crucial long-term issue, so the inter-linked areas of

* Ocean and Atmospheric Sciences

* Palaeoclimatology

need continued support as at present; in particular we can play a useful role in international studies of the climate (global warming) and the ozone hole in the atmosphere.

The basic needs of water, food, energy each have a strong scientific component underlying them, based in turn on Environmental Sciences, Meteorology, Hydrology, Ecology, Physics. What is lacking here, except in the case of energy, is a serious research attempt to relate these issues to community needs; to turn them into real community science. The most crucial element of all is

* Water Studies.

The already excellent work in this area should be extended to a full study of water issues and water policy in all its developmental and environmental aspects, particularly as this affects the underdeveloped areas of the country.

Any serious consideration of resource issues, as well as developing conservation technology and policy, must inevitably lead to the need for research on

* Population Growth: Implications and Policy,

for this growth is going to be the driving mechanism of all our biggest future environmental and resource problems.

29.2.2 Subjects with Particular Suitability

There are a number of subjects that are without immediate clear 'applicability', but are particularly suited to research at this time and place. They have a special claim to our attention for one of a number of reasons.

a) *Because of our location*:

A series of subjects are particularly suitable for research because of our location: Astronomy, Oceanography, Botany, Zoology, Ecology, Geology, Archaeology, Palaeontology, Palaeo-anthropology.

In each case our location and the tremendous natural heritage with which we are endowed gives research in this country a privileged position and opportunity to contribute to world knowledge.

Study of these topics also underlies our potential for developing ecotourism as a significant industry.

b) *Because of our heritage*:
In some cases we have very good groups already in existence working on pure research without any close relation to applications. These should be continued (at a reasonable level of support, forming a minor component of our overall research activity) not because of their utility, but simply because they are good research groups already functioning, with an established reputation based on solid scientific achievement. This applies in Astronomy and some areas of Mathematics and fundamental Physics.

c) *Because of the time*:
There are some subjects which are at this time the most exciting areas of modern research, the 'Hot' topics of modern science where the great breakthroughs are likely to come in the near future.

Some of these are way beyond our scope: modern experimental particle physics, gravitational wave detectors, satellite-based astronomy, to name a few. High temperature superconductivity might be feasible in this country, but we do not have an established research base in the area to make the effort worthwhile in such a competitive field.

However there are some very exciting scientific areas in which we could participate meaningfully on a substantial scale if we wished to do so; specifically,

* the Brain, Consciousness, and Cognition;

* Molecular Genetics and Developmental Biology.

We could form interdisciplinary teams to study each of these areas in depth should we wish to do so, thereby taking part in some of the most important movements of modern science, with practical applications that cannot be predicted in advance, but having the potential to transform technologies in unforeseen new ways.

If we wished to get involved in these areas, we would have to consider very carefully what approach and strategy to follow, as these are very competitive fields; however that fact need not prevent us from making a useful contribution at an international level, with major local spin-offs that cannot be predicted beforehand.

29.2.3 Basic Support Subjects

Finally there are a set of foundational subjects that are a pre-requisite for the rest of the scientific activity discussed here: namely Mathematics, Statistics, Physics, Chemistry, and Systematics within each basic biological subject (Botany, Zoology, Microbiology), these subjects in turn being basic to Ecology and so to Environmental Science. As has been emphasized many times, it is not possible to adequately carry out the support and educational role required of these subjects without high level research activity in each of these areas.

Thus research in these areas should be supported across the board at an appropriate level, taking into account those areas where we have an established track record, but with an emphasis on the following areas that are a solid basis for applications:

* Computational Mathematics,

* Solid State Physics and Modern Optics,

* Polymer Chemistry.

Particularly important in all these subjects is the training they provide students in research techniques and problem-solving.

29.2.4 Interconnection and Relatedness

It is necessary for analysis and presentation to consider the different elements of research in terms of separate subject areas. However overall, the important theme of *interconnection* emerges; workers in each area should be encouraged to understand and relate to the interconnections both of the basic/applied aspects of each subject, and between subjects. This understanding should shape our research work and teaching.

Indeed, Chris Brink suggests that the distinction between pure and applied research is a false dichotomy: one man's theory is another man's application. Lateral research can be both basic and applied: it can be basic in dealing with a problem or concept that does not immediately arise from some aspect of physical reality; applied in attempting to relate this concept to others - to seeking applications in neighbouring fields (Brink 1993).

In the same light, subject boundaries are an artificial division we impose in order to cope with the complexity of the world around us, enabling a basis of understanding because we do not have to grapple with everything at once. However ultimately we need to advance beyond these boundaries and tackle integrated themes, as happens in ecology, environmental studies, and interdisciplinary subjects.

29.3 Specialist and Interdisciplinary Themes

The tension that becomes very apparent in working through the areas discussed in this document is that between specialist expertise and integrative ability.

Science is essentially based on specialists who understand the details of the foundational subjects (maths, statistics, physics, chemistry, measurement and analytic processes) very well. Its useful applications depend on people who understand the broad interactions that result from complex situations, as in ecology and environmental science.

Ideally we would like to educate people who combine both kinds of talents in one person. However the fact is that people with that capacity are comparatively rare; indeed one can suggest there are separate personality types that are naturally expert in the one kind of work or the other, with relatively few scientists who have the natural ability to simultaneously be expert in both.

29.3.1 Research Matrix

The challenge for scientists and science administrators then is how to encourage both kinds of work to proceed in a symbiotic way, creating structures that enable the individual subjects to be developed in their own right, and that also encourage and make possible their successful integration to solving the urgent problems of society around us. It is study of these interdisciplinary themes that is the lynchpin of useful science (cf. the previous sections).

Researchers should be able to pursue understanding of their own subject, according to independent evaluation of the quality of their work, but should also be encouraged to join application-area teams. These should be implemented by a committee funding and supporting such teams properly, and enabling links to the relevant application bodies (industry, engineering, communities) where necessary.

The basic proposal, then, is that we need to structure research in a matrix with the following components:

* experts in particular base subjects (physics, chemistry, applied mathematics, etc.),

* experts in integrated studies (environmental management, development studies, etc.);

these people would work and study in their own area much of the time, but would be brought together from time to time, or on a long-term basis, in

* integrated research teams or task forces,

focused on tackling particular application problems. These provide a matrix of 'pure' and 'applied' skills, appropriate to tackling the problem at hand.

Thus we would encourage research workers who are specialist and also those who are generalists, but in both cases would preferentially support those who are willing and able to work effectively in such integrated research teams.

29.3.2 Interdisciplinary Themes

There are particular interdisciplinary themes that should be picked up in the overall research programme.

a) *Developmentally important*:

Of fundamental developmental importance to science and technology in the future is research into

* Science Education,

where there is a need to impart skills and abilities as well as a general understanding of the nature and excitement of science.

The theme of this research is demystifying science and making it accessible. While most of this work would be devoted to researching optimal educational methods and organisation at school and tertiary institutions, some of it would be devoted to the issue of building up a culture and understanding of science in the public at large.

A particularly powerful way of working toward achieving this understanding and imparting some scientific ability is through

* Informal Sector Participation in Research Programmes.

These are implemented by devising research projects where the public, and in particular school children, can - after suitable training, and with appropriate quality checks - take part in providing useful data.

A number of areas where this is possible have been identified in this document (see section 24.1.4). An integrated schools programme should be established to develop and support such projects.

Also of importance is the subject of this document, namely

* Science Policy Research,

relating both to the science and technology (S&T) area, and to science for its own sake.

b) *Important in making value choices*:
There are a number of topical areas (animal experiments, gene experimentation and biotechnology) where science and its implementation raises serious - and non-trivial - ethical and value issues. In order to take this seriously, we need research into

* Values and Ethics in Science and its Applications.

Additionally, such research underlies a proper foundation for the value-choices determining the nature of environmental management decisions.

c) *Culturally vital*:
Finally there are some areas that should be pursued in order that we have a culturally vibrant and aware life. Because of the impact of science on modern thought, we should maintain some research on

* Science, Philosophy, and Life,

considering the nature and limits of science, and its implications for a plausible modern world view. This leads to consideration of the implications of theories of the origin of the universe, evolutionary theory, socio-biology, and so on.

We use the word 'modern' advisedly here. Part of the aim of this work could be to consider to what extent - if at all - ideas such as 'deconstruction' and 'post-modernism' have relevance to a world view that takes modern science seriously.

29.4 Research as a Way of Life

Following the recommendations above will require a substantial - but not excessive - direction of resources to research projects. It may be claimed by some that from the viewpoint of the general public, this is a mis-use of resources, for research is an esoteric pursuit without practical value. A perusal of this document will show that this viewpoint is fundamentally in error. However the issue goes beyond the fact that research underlies traditional and modern technologies, and our understanding of ecological systems and the environment. The fundamental point in the end is that research is not limited to scientists and academics: rather when properly perceived, *it is a way of life*, indeed the only viable way of life for each one of us.

The point is that all learning is based on research - trying out what works and what does not, and modifying our behaviour according to the results of our observations and experience. Thus it in fact underlies our management of our personal lives, sporting activities, work, the way we run our society; indeed it is central to properly perceived organisational theory and practice (Senge 1991, Ellis 1991); and above all is central to the way children learn.

This observation is fundamental to how we should structure our activities. In particular it applies to teaching and learning at school. Properly construed, *training in research is the primary task of the teacher at school* (as well as at universities and other tertiary institutions). Thus training in research should be the central theme of teacher training colleges and university educational faculties.

Hence in the end, the fundamental point is that, at its foundations, *a culture of learning is a culture of research.* That is the ultimate aim of our educational activities. The scientific research activities promoted in this document are a natural outcome of, and basic support for, such a culture of research and learning. This is central to all education, and in particular to science and technology education.

29.5 The Whole Package

There are exciting challenges and opportunities facing us. An overall research package in the sciences, that presented here or something like it, will be an important element in meeting these challenges. It should be supplemented by similar research proposals in other important areas (technology and engineering, health and medicine, agriculture, the social sciences) so that research overall takes place according to a coordinated and productive plan.

At present we spend a reasonable amount on general science research; this level should at least be maintained in the short term (understanding that the research effort will be given suitable overall direction, by a plan something like that put forward in this paper). Preferably it should be substantially increased by re-allocating monies from the grand apartheid-era projects, on which huge sums have been expended.

In any event science research support should be increased in the long term, as should research efforts in industry, which are at present quite inadequate for a modern economy. We could easily find the requisite amount by redirecting money from 'defence' expenditure, indeed we would then be utilising that money for its proper purpose of building up a sound future for our citizens. This should be controlled by committees that are not toothless talking shops; thus at least some of them should be made responsible for specific funds and held publicly accountable for the use of these funds.

The overall support advocated here is well within our grasp; indeed it is essential for our future welfare.

Chapter 30

Contributors & References

Coordination of this draft document has been by G F R Ellis (President of the Royal Society of South Africa). As explained at the beginning, it has only been possible because of the thoughtful responses of many people to a request for constructive views on the topics discussed.

30.1 Contributors & Comments

I should like to thank the following who sent in contributions or comments that have helped shape the discussion and proposals in the document (but they are not responsible for its final form; they may or may not agree with what is proposed here):

L Alberts
B R Allanson
C Allen
D Aschmann
E Blake
M C Berman
G E Blight
J C A Boeyens
W Bond
G Branch
C Brink
R V Dingle
S E Drewes
S Driver
A Eberhard
M W Feast
J G Field
A O Fuller
C F Garbers
W Gevers
A V Hall
M A Hellberg
L Nassimbeni
P E Odendaal
J Parkington
O W Prozesky
R E Raab
B D Reddy
D Reitmann
B Schroeder
M W J Scourfield
L Y Shackleton
J P F Sellschop

F Brooks
M E Brown
G B Brundrit
M N Bruton
J Bull
G D Campbell
C Comrie
D Cook
R Cowling
D J Crafford
T Crowe
B R Davies
J Day
M J de Wit
B J Huntley
P Jacobs
J Juritz
H Klump
M Le Roex
R Lindsay
M I Lucas
J R E Lutjeharms
A McLachlan
P Machanick
J B Martin
J Midgeley
R P Millar
F R N Nabarro
L V Shannon
R Siegfried
J D Skinner
M G Soltynski
H Spencer-Jones
J A Thomson
M Tredoux
R Viollier
J H van der Merwe
G von Gruenewaldt
A D M Walker
B Warner
D R Woods

In particular, I should like to thank the following for contributions of considerable length, that in some cases virtually amounted to writing an entire section:

E Blake (Computer Science), C Brink (Mathematics), W Bond (Botany), R J Bull (Chemistry), R Cowling (Biome projects), T Crowe (Ornithology), B R Davies (Hydrology), J Day (Aquatic Ecosystems), M de Wit (Earth Sciences), R V Dingle (Marine Geology), A Eberhard (Energy Research), M Feast (Astronomy), M Hellberg (Physics), J Juritz (Statistics), H Klump (Biochemistry), M Lucas (the Antarctic), J R E Lutjeharms (Oceanography), P Machanick (Computer Science), J B Martin (Information Technology), J Midgeley (Forestry Ecology), F R N Nabarro (Materials Science), L Nassimbeni (Chemistry), J Parkington (Archaeology), B D Reddy (Computational Mathematics), J P F Sellschop (Nuclear Physics and NAC), L Shackleton (Marine Sciences), V Shannon (Marine Science), R Siegfried (Zoology), J A Thomson (Microbiology), R Viollier (Physics).

In many cases these contributions were based on discussions by the author with other colleagues; I thank them also.

We received comments from the South African Association for the Advancement of Science and the Astronomical Society of Southern Africa, and communications from various other scientific societies (the Institute of Physics, Biochemical Society, Society for Geography, Die Suid-Afrikaanse Akademie vir Wetenskap en Kuns, the South African Association of Botanists). These have also been taken into account in drawing up this document.

While this document has the broad support of the Council of the Royal Society, as emphasized before, it does not represent their official position or that of the Society. Most comments on the previous draft version have been positive, but not uniformly so. In particular, negative comments have been received from some nuclear physicists regarding the sections on NAC; these sections have been modified in the light of those comments. Prof. F R N Nabarro has commented that the document is "sufficiently detailed to be tedious, but insufficiently detailed to be compelling". After considering these various comments, Council has decided nevertheless to go ahead with publication as a discussion document, in the belief that it can serve a useful purpose.

30.2 References

African Academy of Sciences (1989) *Environmental Crisis in Africa: Scientific Response.* Academy Science Publishers, Nairobi.

ANC (1990) *Towards a Technology Policy for South Africa.*.

AS&TS/JCSS/SAVI (1993): *Education Policy for Technology Initiative.*

G Baker (Ed.) (1976): *Resources of Southern Africa: Today and Tomorrow* AS&TS, Johannesburg.

I Barbour (1993): *Ethics in an Age of Science and Technology.* Harper, San Francisco.

J H Barkow, L Cosmides, & J Tooby (1992). *The Adapted Mind.* Oxford University Press.

W F Baxter (1974): *People or penguins. The case for optimal pollution.* Columbia University Press.

BEP (1992): Benguela Ecology Programme Phase III Science Plan.

C Brink (1993): Mathematics: A Lateral Approach. Inaugural Lecture, University of Cape Town, 26 May 1993. (New Series No. 176.)

G Branch and M Branch (1987): *The Living Shores of South Africa.*

J Bronowski (1976) *The Ascent of Man.* BBC Publications, London.

L R Brown (1993): A New Era Unfolds. In *State of the World 1993*, WW Norton and Co. New York.

M N Bruton (1989): *SA Journal of Science* **85**, 348-350.

M N Bruton (1992): *SA Journal of Science* **88**, 554- 557.

Carnegie Commission (1992): *Partnership for Global Development. Clearing the Horizon.* Carnegie Commission of Science, Technology and Government, New York.

Carter Centre (1993): *Conference on Global Development Cooperation.* Carter Centre of Emory University, Atlanta.

D Cooper (1993): *Science and Technology - A 'Hidden Crisis' of Post-Secondary Education in South Africa? Shape and Size of S&T in the Technikons.* African Studies Centre, UCT.

COPUS (1992): *COPUS looks forward. The next five years.* Committee on Public Understanding of Science, c/o The Royal Society, Carlton House Terrace, London SW1Y 5AG, UK.

D W H Cousens, E Braune, & F J Kruger (1988): *Surface Water Resources of South Africa: Research Needs.* Water Research Commission, Pretoria.

CSP (1978): *A description of the Fynbos Biome Project.* SA National Scientific Programmes Report No 28 (CSP/CSIR).

R. Cowling (Ed.) (1992): *The Ecology of Fynbos. Nutrients, Fire, Diversity.* Oxford University Press.

J M Cumming (1990): *Technical/Industrial Education Planning for a Developing Region of Southern Africa.* Australasian Journal of Engineering Education, Vol 1, No 1, p 29.

H E Daly (1987): The economic growth debate: What some economists have learned but some have not. *Journ Env Economics and Management.* **14**, 323.

P J Davis & R Hersh (1981): *The Mathematical Experience.* Birkhauser.

J Day, R Siegfried, G N Louw, & M L Jarman (Ed) (1979): *Fynbos Ecology: a Preliminary Synthesis.* SA National Scientific Programmes Report No 40. (CSP/SIR, Pretoria).

M de Wit (1993): The future of the geological sciences in South Africa. Geology Department, University of Cape Town.

Y R Dommerges (1989): How can Nitrogen fixation contribute to the maintenance and improvement of soil fertility. In *Environmental Crisis in Africa: Scientific Response* (African Academy of Sciences, Nairobi), pp. 70-75.

J Sholto Douglas & R A de J Hart (1976): *Forest Farming.* Watkins, London.

M Dow (1989): Issues in research and institutional development related to drought, desertification and food deficit in Africa. In *Environmental Crisis in Africa: Scientific Response* (African Academy of Sciences, Nairobi), pp. 30-56.

A Eberhard & A Williams (1988): *Renewable Energy Resources and Technology Development in Southern Africa.* Elan Press.

ECOFOCUS (1993): Keeping a close watch on global climatic change. Volume 2, No2, pp. 3-7. FRD, Pretoria.

EDRC (1992): *EDRC the first three years: 1989 to 1992.* Energy Development Research Centre, UCT

EDRC (1993): *Project Proposal: Energy Policy for New South Africa.*. Energy Development Research Centre, UCT. See also *EPRET Newsletter.*

G Ekama (1992): Municipal waste Treatment in South Africa: Past and Future. Inaugural Lecture, UCT.

G F R Ellis (1974): *On understanding the world and the universe.* Inaugural lecture UCT

G F R Ellis (1991): The science Faculty in the next decade. *SA Journal of Science*, **87**, 564-568.

G F R Ellis (1991a): *Organisation and Administration in a Democratic Era.* Book draft.

G F R Ellis (1993a): Priorities in South African Science in a changing Economic and Political context. *Trans Roy Soc S A* **48**, 351-373.

G F R Ellis (1993b): *Before the Beginning.* London, Bowerdean/Boyars (Distributed by Media Publishing, Johannesburg).

G F R Ellis (1993c): The School Maths Syllabus. Preprint, Department of Applied Maths, UCT.

EMG (1992): *Towards Sustainable Development in South Africa.* Environmental Monitoring Group (Western Cape).

C Flavin & J E Young (1993), Shaping the next Industrial Revolution. In *State of the World 1993*, WW Norton and Co. New York.

Faculty of Science (1980): *Applied Research in the Science Faculty of the University of Cape Town.* UCT Science Faculty 1988.

FORESTEK (1994): Quarterly Newsletter of the Division of Forest Science and Technology (CSIR, Pretoria), Vol. 3, No. 1.

FRD (1990): *Marine Science and Technology in South Africa.* Foundation for Research Development, Pretoria.

FRD (1991): *Rural Poverty Alert.* FRD Report Series.

FRD (1991a): *Science Policy in South Africa. Government Funding of Academic and Related Research.* FRD Pretoria.

FRD (1992): *Strategic Priorities for Science. Transforming subjective visions into Knowledge.* FRD Pretoria.

FRD (1993): *FRD Council Report 92-93.* FRD, Pretoria.

FRD (1993a): *Scientech: Winning People.* FRD, Pretoria.

FRD/ICSU: *International Council of Scientific Unions and the South African Connection.* FRD, Pretoria.

R F Fuggle & M A Rabie (1983): *Environmental Concerns in South Africa: Technical and Legal Perspectives* Juta and Co, Cape Town.

E Geake (1993): *New Scientist*, 28 August, pp.18-19.

D Grayson (1992): *Workshop on research in science and mathematics education*. Proceedings. University of Natal, Pietermaritzburg.

J J Grobler (1992): Status of Mathematical Research in SA. *SAMS Notices* **24**, no 2, p112-121

J A Harrison (1988): *Southern African Bird Atlas Project: Instructions.* SAFRING, University of Cape Town.

J A Harrison (1992): The Southern African Bird Atlas Project: five years of growth. *S A Journ of Science*, **88**, 410- 413.

M T Hoffmann (1988): The rationale for Karoo grazing systems: criticism and research implications. *SA Journ Sci* **84** 556-559.

B Huntley, R Siegfried & C Sunter (1989): *South African Environments into the 21st century*. Human and Rousseau, Tafelberg.

ICSU (1993): *Science International*. International Council of Scientific Unions Newsletter, December 1993.

IDRC (1993): *Towards a Science and Technology Policy for a Democratic South Africa.* Mission Report: July 1993. International Development Research Centre Regional Office for Southern Africa (Johannesburg).

Indicator (1990): Rotating the Cube: Environmental strategies for the 1990's. *Indicator SA* April.

IUPAP (1993): *Reports, 1990-1993.* International Union of Pure and Applied Physics.

R Lal (1989): Soil and Water conservation and management research in tropical Africa. In *Environmental Crisis in Africa: Scientific Response* (African Academy of Sciences, Nairobi), pp. 76-87.

R Lindsay (1993): Position of the National Accelerator Centre (NAC). University of Western Cape

M I Lucas & J A Lindesay (1991): Global climatic change: Environmental and climatic links between Antarctica and South Africa. *S Afr J Antarct Res*, **21**, 193-219.

M I Lucas, F R E Lutjeharms, J G Field & C D McQuaid (1993): A new South African research programme in the Southern Ocean. *SA Journ Sci* **89**, 61-67.

J E Lutjeharms & J A Thomson (1993): *S A J Sci* **89** 8-14.

MRC (1993): *Guidelines on Ethics for Medical Research.* South African Medical research Council.

F R N Nabarro (1994): Materials science and engineering in the development of South Africa. Draft document for the SA Institute of Physics.

National Academy (1974): *More water for arid lands.* National Academy of Sciences, Washington DC.

National Academy (1984): *Computational Modelling and Mathematics Applied to the Physical Sciences.* National Academy Press, Washington DC.

NEPI Science Curriculum Group Report (1992): S Levy (Edunet, P O Box 1833, Houghton).

NSF (1990): *Research Briefing Panel on Order, Chaos and Patterns: Aspects of Non-Linearity.* National Science Foundation.

T R Odhiambo (1993): Responsibilities of a Scientist in the Developing World *Whydah* Vol 3, No 3, June 1993 p1.

T R Odhiambo & T T Isoun (Ed.) (1989): *Science for development in Africa: Proceedings of the consultation on the management of Science for development in Africa.* Academy Science Publishers, Nairobi, 1989).

B N Okigbo (1989): Agroforestry. In *Environmental Crisis in Africa: Scientific Response* (African Academy of Sciences, Nairobi), pp. 96-110.

SNC Okonkwo (1992): Biotechnology and natural resources management: *Whydah* **3** No 2, 1-10.

On Stream, Journal of the Umgeni Water/Amanzi Project (P.O. Box 9, Pietermaritzburg 3200).

PANOS (1987): *Towards sustainable development.* The Panos Institute, London.

PANOS (1990): *Electricity for rural people.* Panos Publications, London.

S Parker: *Studies in School Ecology.* Science Education Centre, University of Rhodesia.

G Pastoll (1992): *Tutorials that Work. A guide to running effective tutorials.* Juta, Cape Town.

A I Payne J A Gullind & K H Brink (1987): The Benguela and Comparable Ecology Systems. *S A Journ Marine Sci* **5** (Marine Fisheries Research Institute).

A I Payne K H Brink K H Mann & R Hibarre (1992): Benguela Trophic Functioning. *S A Journ Marine Sci* **12** (Marine Fisheries Research Institute).

PRB (1992): *The UN long range population projections: What they tell us.* International Programs, Population reference Bureau, 1875 Connecticut Avenue NW, Washington DC 20009, USA.

A Pouris (1989). Strengths and weaknesses of South African science. *S. Afr. J. Sci.* **85**: 623-626.

A Pouris & A Pouris (1993), *Equipping South African Science.* FRD.

J P Reaganold, R I Papendick, & F J Parr (1990): Sustainable Agriculture. *Scientific American* June 1990, pp.72-78.

A Rebelo (1992): *Protea Atlas Manual. Instruction book for the Protea Atlas Project.* National Botanic Institute, Kirstenbosch, Private Bag X7, Claremont 7735.

D J Rose, J H Gibbons, & W Fulkerson (1972): Physics Looks at waste management. *Physics Today* Feb 1972, 32-41.

RSSA (1978): The effects of population growth on South Africa. *Trans Roy Soc SA* **43**, Part 1.

SANCOR (1993): *SANCOR Newsletter,* September 1993 (Special Edition). Issued by the FRD, Pretoria.

R J Scholes & Walker (1993). *Nylsvlei: The Ecology of a South African Savannah.* Cambridge University Press.

R E Schulze & R P Kunz (1993): Climate Change Scenarios for Southern Africa: 1993. Department of Agricultural Engineering, University of Natal (Pietermaritzburg). Compiled at the request of the South African Global Climate Change Committee.

Scientific American (1986): Special Issue of *Scientific American* on Advanced Materials (October, 1986).

P M Senge (1991): *The Fifth Discipline. The Art and Practice of the Learning Organisation.* Doubleday Currency, New York.

B Smith & L Bohm (1994): Cyclotron Future. *Nature* **367**, 676.

K A Smith (1984): Industry-university research programs. *Physics Today* February 1984, 24-29.

SPRU (1992): Science Policy Research Unit Annual report: 1991-1992. University of Sussex at Brighton.

R Stauth (1983): *Environment Evaluation Manual.* UCT School of Environmental Studies Research report No. 51.

L A Steen (1980): *Mathematics Today.* Vintage Books.

I Stewart (1987): *The problems of Mathematics.* Oxford.

R S Stobie, I S Glass, & D H Buckley (1993). South African Large Telescope: A Proposal for Funding. South African Astronomical Observatory, P O Box 9, Observatory 7935, Cape Town.

N C Thanh & A S Biswas (1990): *Environmentally sound water management.* Oxford University Press, Delhi.

P Theron (Ed.) (1992): *Proceedings of the ANC National Meeting on Electrification.* ANC Department of Economic Planning/Centre for Development Studies.

E W Thulstrup (1992): *Improving the quality of Research in Developing Country Universities.* PHREE Background Paper Series. World Bank Education and Employment Division, Population and Human Resources Department, 1992.

J C Tothill (1989): Agroforestry in African Crop/Livestock Farming systems. In *Environmental Crisis in Africa: Scientific Response* (African Academy of Sciences, Nairobi), pp. 88-95.

L G Underhill T B Oatley & J A Harrison (1990): The Role of Large-scale data collection projects in the study of Southern African Birds. *Ostrich* **62**, 124-148.

UNESCO (1986): *The Seville Statement on Violence.* The Seville Statement Support Network, Wesleyan University Psychology Department, Middletown, CT 06549-0408, USA.

U.S. National Research Council (1992): *Computing the Future.*

D van Heerden (1986): *Friemersheim: A Profile.* SALDRU Working Paper no 74, South African Labour and Development Research Unit, UCT.

T G Whiston (1993): *Research Policy in the Higher Education Sector of South Africa.* Science Policy Research Unit, University of Sussex, Falmer, Brighton.

P A Whitelock (1993): *Opportunities in Astronomy in South Africa.*. SAAO.

K-H Winkler *et al* (1987): A numerical laboratory. *Physics Today,* Oct 1987, pp.28-37.

N Zabusky (1987): Grappling with complexity. *Physics Today.* Oct 1987, 25-27.

* * *