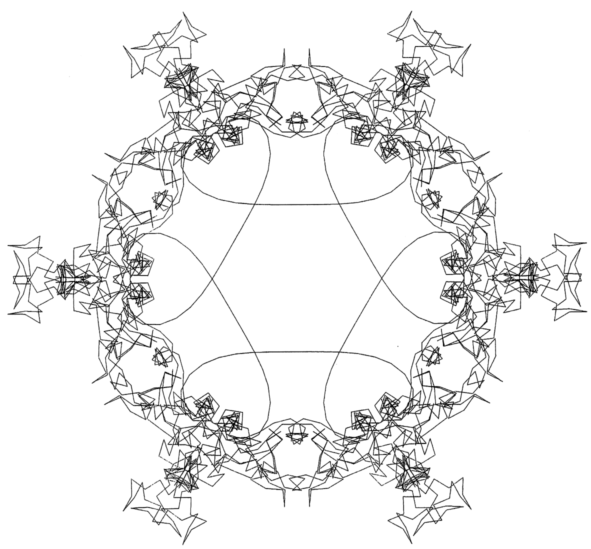
**National Board of Employment, Education and Training**

**Australian Research Council**

**Discipline Research Strategies**

# Mathematical Sciences

## Adding to Australia



**Prepared by a Working Party appointed by the National Committee for Mathematics of the Australian Academy of Science**

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The scope of this review is the 15 years 1995–2010. The cover graphic is the polygon of two thousand and ten segments sequentially connecting the points in the complex plane given by the partial sums of the exponential sum

$$\sum_{n=1}^{2010} e^{2\pi i n^3/2010}$$

# Foreword

Recognizing that the active involvement of the research community is essential to the formulation of good research policy, the Australian Research Council (ARC) encourages peak bodies to commission research strategies in their disciplines. The purpose of these strategies is to enable the sectors within a discipline—those who perform research, those who fund or commission it, those who use the results or employ research trained postgraduates—to all participate in developing a picture of where the discipline should be in yen to fifteen years time, and a plan for getting there.

The Australian Research Council is willing to facilitate the initial stages of strategies, and to recommend a significant amount of funding from the Evaluation Program, which is administered by the Department of Employment, Education and Training. However, the Council does not wish to control the process or own the result. The Council's interest in the outcome of the exercise is focussed mainly on the three areas for which it has primary responsibility—research in the higher education sector, basic research and research training. While the ARC wants to know what each discipline sees as its future, it must have regard to the competing needs of the wide range of disciplines that are supported through the program on which it advises government.

Each discipline will have its own reasons for undertaking a strategic review, and the Council does not seek to impose a narrowly conceived model. The ARC does, however, encourage those developing strategies to take a wider view of the discipline than that determined by the Council's interests. If support can be obtained from other agencies and government departments, and from the users of research and the employers of research-trained staff, it is clearly desirable to develop as complete a picture as possible of research and research training in a discipline. The ARC believes all major stakeholders should contribute to the cost of a strategy—in proportion to their means. Finally, if strategies are to be useful inputs into the policy process, they must indicate in detail what a discipline's priorities are.

*Mathematical Sciences: Adding to Australia* is the sixth research and research training strategy to be produced with support from the Evaluation Program. The report demonstrates with clarity the extraordinary way in which this most fundamental of disciplines is intertwined with other disciplines, and with the life of the nation. It makes a persuasive case that mathematical sciences at an advanced level play a crucial role in the nation's economic competitiveness and social justice issues. The report presents a well-balanced set of recommendations to guide the development of the discipline into the next century. I urge all the players to consider the findings and recommendations carefully and to commit themselves to implementing their responses.

M H Brennan AO
Chair
Australian Research Council

January 1996

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# Preface

From time to time, the Australian Research Council initiates and co-sponsors reviews of major disciplines. The reviews, undertaken in collaboration with stakeholders, identify 10-15 year goals for the relevant discipline and propose suitable strategies to reach the goals.

This review of the mathematical sciences follows similar ARC reviews of chemistry, physics, the earth sciences, education and astronomy. Our aim was to investigate

> *research activities in the mathematical sciences and*
> *provision of high level mathematical services to the nation*

where 'mathematical' is interpreted broadly to include mathematics in its own right, the various branches of applied mathematics, statistics, operations research, actuarial science and computational mathematics. The full Terms of Reference for the review follow the Executive Summary.

This review involved

- the Australian Research Council as initiating body
- the National Committee for Mathematics of the Australian Academy of Science as overall co-ordinating body
- a Working Party appointed by the National Committee for Mathematics as executive body
- an Advisory Council which helped to develop the Terms of Reference and provided feedback on draft findings and recommendations

The scope of this review of the mathematical sciences was unprecedented in Australia and the inputs were extensive. The Working Party received inputs by

- distribution of over 600 questionnaires to academic departments, CRCs, CSIRO Divisions, professional associations and other Australian enterprises
- hearings in 8 separate cities (10 academic hearings, 10 others for industry); at these hearings we received submissions from over 40 academic departments and well over 50 non-academic enterprises and organisations
- other site visits and meetings held at various stages of the review

In addition, as befits a thoroughly international activity, we acquired beneficial advice from landmark overseas-sourced reports. A full list of submissions is given in the Appendix.

The review had a number of sponsors including the Australian Research Council, academic departments, CSIRO, BHP Research, professional associations and the NSW Office of Economic Development. Further details are given in the Appendix.

The Working Party for the review was

Professor A J van der Poorten, Macquarie University (Chairman)
Dr N G Barton, CSIRO (Executive Officer and Editor)
Professor M N Barber FAA, University of Western Australia
Professor T C Brown, University of Melbourne
Professor D W Robinson FAA, Australian National University
Dr E H van Leeuwen, BHP Research

Ms J B Lain (CSIRO) acted as Secretary to the Working Party

The Advisory Council for the review was

Professor C E Praeger, University of Western Australia (Chair)
Dr D Dickson, University of Melbourne
Dr D Gibson, ASTA
Dr J L Hopper, University of Melbourne
Associate Professor K Horadam, RMIT
Professor G C Leder, La Trobe University
Associate Professor P B Lochert, Monash University
Mr P McMullan, Electricity Supply Association of Aust Ltd
Mr T J Pettigrew
Dr R L Sandland FTSE, CSIRO Division of Mathematics and Statistics
Dr B Sawford, Environment Management Industry Association
Professor I H Sloan FAA, University of New South Wales
Dr L White, DSTO

The National Committee for Mathematics has the following members

Professor I H Sloan FAA (Chairman)
Professor G I Gaudry
Professor C C Heyde FAA
Associate Professor P Lochert
Professor D W Robinson FAA
Ms J Thomas
Professor G C Wake

# Executive Summary

This review examines the health of research in the mathematical sciences in Australia. The review also investigates the provision of high level mathematical services, and demonstrates how the nation gains benefit from its investment in this discipline.

Mathematics is the study of measurement, forms, patterns, variability and change. It evolved from our efforts to understand the natural world. Its roots go too far back in prehistory to trace, but an unbroken chain of development has continued for more than two thousand years since Greek civilisation at the time of Euclid. The end of this chain, modern mathematical science, is in its own right a supreme creation of the human intellect; it is also critical for economic competitiveness, and a basis for investigations in many fields.

Over the course of time, the mathematical sciences have developed a rich and intrinsic culture that feeds back into the natural sciences and technology, often in unexpected ways. The mathematical sciences now reach far beyond the physical sciences and engineering; they reach into medicine, commerce, industry, the life sciences, the social sciences, and to every other application that needs quantitative analysis. Their influence has been vastly enlarged by the advent of modern computers. Computer use in problem solving, simulation and decision making relies on powerful computational algorithms derived from new mathematical developments.

At the launch of a major international meeting a few years ago, the then President of France spoke in the context of mathematics of "la necessité d'une politique de la science soucieuse du long terme, attentive à l'équilibre entre recherche, enseignement, économie"[1]. In our words, he is asserting that there is interdependence between research within the mathematical sciences, the application of these sciences in other disciplines, and their teaching. Each of these nourishes the others with ideas, methods and inspiration.

Research in the mathematical sciences used to be primarily undertaken on an individual basis. Collaborative research has now become more widespread, perhaps to the extent that it is more common than individual research. Taken together, individuals and groups pursuing research in the mathematical sciences constitute a human and intellectual resource of utmost national significance.

[1] F. Mitterand, *message for the colloquium "Future Mathematics"* (December, 1987) pointed to "the need for a politics of science aware of the long term, and conscious of a correct balance of research, teaching and economic factors".

This review is also concerned with Australia's performance in the delivery of high level mathematical services. The review finds unequivocal evidence that, as an economic and social instrument, advanced mathematical services relying on the mathematical sciences are critically important to Australia.

The mathematical sciences are universal. Some of the words above are taken from the National Policy Statement of the American Mathematical Society, yet their relevance to the Australian context is manifest. Elsewhere, we make extensive use of documents developed by the Society for Industrial and Applied Mathematics in the USA.

The present Strategic Review of Mathematical Sciences Research and Advanced Mathematical Services in Australia has four principal findings and 20 recommendations.

## Principal Findings

**1.** It is essential for Australia to have a sound research base in the mathematical sciences for the following reasons:

- to be able to respond to new research ideas and opportunities
- to capture benefit through collaborative research and downstream technology transfer
- to educate future mathematical sciences graduates
- to contribute to the economic and cultural strength of the nation
- to benefit from international developments

In general, Australia possesses a sound research base, although certain sub-disciplines, among them operations research and financial mathematics, need to be strengthened.

**2.** The mathematical sciences are critical to Australia's economic competitiveness and quality of life, and will become more so. The mathematical sciences are generic and enabling technologies. They are essential to the prosperity of many value-adding industries in Australia.[2]

[2] These remarks endorse and confirm the relevance to the Australian context of the findings of a major US-sourced report on the importance of the mathematical sciences to modern economies: *Mathematical Sciences, Technology and Economic Competitiveness*, James G Glimm (ed.), Board on Mathematical Sciences, National Research Council, National Academy Press, Washington, DC, 1991.

**3.** The mathematical sciences make a vital contribution to many fields of research and endeavour. The importance of this contribution needs further emphasis because

- much work in the mathematical sciences is multi-disciplinary in nature
- there is a spillover of concepts and techniques from the mathematical sciences into other disciplines, particularly through methods and software widely used in those disciplines
- researchers in many other disciplines (including the social sciences) who would not describe themselves as mathematical scientists nonetheless make extensive use of mathematical and statistical concepts

**4.** The mathematical sciences profession in Australia faces a number of major challenges:

- improving the image of the profession to match its importance and effectiveness
- balancing an age distribution which is currently skewed by the growth in the profession in the late 1960s and 1970s
- redressing the gender imbalance at senior levels
- attracting good undergraduate students into mathematical sciences courses
- increasing opportunities for postdoctoral level researchers
- broadening the funding base for research
- educating potential users to the value of the mathematical sciences
- improving technology transfer programs and associated educational programs, particularly for SMEs (small to medium enterprises)

If these challenges are not addressed successfully, there will be significant diminution in Australia's capabilities in the mathematical sciences, to the detriment of the nation.

# Terms of Reference

To prepare a strategy for the development of research in the mathematical sciences, including the provision of advanced mathematical services, in Australia over the next 10-15 years.

## A. Mathematical Sciences Research

To make recommendations on research in the mathematical sciences that advance those sciences and contribute to the scientific, economic and cultural welfare of Australia.

1. To determine the degree to which a strong fundamental research base is required in all branches of the mathematical sciences in Australia and recommend on future support of this research.
2. To identify areas of research strength and weakness in the mathematical sciences in Australia and recommend necessary policy or funding changes.
3. To evaluate benefits drawn from interdisciplinary research in which the mathematical sciences contribute and recommend how to enhance those benefits.
4. To evaluate benefits gained from participation in international mathematical research programs and recommend actions to enhance those benefits.

## B. Provision of Advanced Mathematical Services

To recommend on the provision of advanced mathematical services to business, industry and other users in Australia.

1. To examine how advanced mathematical services contribute to other fields of endeavour, and to assess the national benefits from Australia's investment in the mathematical sciences.
2. To determine the areas of the mathematical sciences most used by business and industry and identify those most likely to be needed in the next decade.

3. To identify strengths and weaknesses in the provision of advanced mathematical services in Australia.
4. To recommend policy and funding changes that will
   (a) enable the mathematical community to offer better mathematical services to users, and
   (b) facilitate the uptake by industry and other users of advanced mathematical services.

## C. Infrastructure

To make recommendations for resource allocations to implement the recommendations in **A** and **B** above.

1. To investigate human resource issues associated with research in the mathematical sciences and the provision of advanced mathematical services, and to make recommendations to ensure an adequate supply of trained people will be available to meet the nation's needs over the 10-15 year scope of this review.
2. To assess current PhD programs in the mathematical sciences in Australia and make recommendations for improvement.
3. To assess educational programs associated with the delivery of advanced mathematical services and make recommendations for improvement.
4. To examine how research in the mathematical sciences and the provision of advanced mathematical services have changed as a result of developments in computing, communications and information technology, and to recommend on further changes over the next 10-15 years.
5. To examine current government support for mathematical sciences research and the provision of advanced mathematical services, and to recommend appropriate strategies and priorities for future support, quantifying any increase in required funding.

# Recommendations

A brief justification or background statement precedes each recommendation. Further details for each recommendation are given in the bulk of the report.

The nature of mathematical sciences research is continually changing. One notable feature is that sub-disciplines of mathematics that previously were investigated without applications in mind now have important applications. An obvious example is the use of number theory and group theory in cryptography. The old usage of the terms 'pure' and 'applied' mathematics is inappropriate and a source of confusion.

**Recommendation 1**

- ☐ In addition to the Field of Research classification, research activities in the mathematical sciences should be described by the Australian Standard Research (Type of Activity) Classification, namely basic research (pure or strategic), applied research and experimental development.

[**Mathematical sciences researchers, Heads of Department, Deans**]

In submissions to the Review and through its site visits, the Working Party formed the view that there was a significant weakness in the research framework underpinning Operations Research (see footnote 2 in Chapter 1 for a definition). The Australian Research Council has a variety of mechanisms which can address this situation.

**Recommendation 2**

- ☐ The Australian Research Council is encouraged to designate the field of Operations Research as a priority area for ARC grants, particularly as a Key Centre of Teaching and Research.

[**ARC**]

The Working Party believes that the nation's mathematical scientists have much to gain by engaging more fully with SE Asia and the Pacific Rim. Benefits are expected for both basic and applied research.

**Recommendation 3**

- ☐ To promote Australia's capabilities, mathematical sciences researchers are encouraged to give higher priority than is now customary to participation in scientific conferences in SE Asia and the Pacific Rim.

[**Mathematical sciences researchers, Professional Societies**]

It is essential that some consulting work be undertaken by some mathematical sciences departments. This consulting work should be viewed in a similar light to service teaching, namely that it is an important part of the profession. Consulting encourages the transfer of mathematical sciences technology to users outside the universities and thereby helps to develop a culture of innovation in Australia. It also offers a valuable opportunity to diversify funding sources. In view of these benefits, consulting should be appropriately managed and rewarded.

**Recommendation 4**

- ☐ Universities should enhance their mechanisms for recruiting and rewarding academic staff who, through consulting and similar activities, provide advanced mathematical services to external customers. Consulting should be fully costed, and it should be managed through departments and not on an individual basis.

[**AVCC, Deans**]

For their continued well-being, the mathematical sciences are dependent on inter-disciplinary collaboration and technology transfer to users. Mathematical sciences departments should establish mechanisms to receive external advice about their courses and prospective activities. We therefore recommend that

**Recommendation 5**

- ☐ All mathematical sciences departments should have external advisory mechanisms to assist in the development of strategic objectives, to inform the department about research opportunities, and to get external feedback on the suitability of existing and proposed courses.

[**Heads of Department, Deans**]

The mechanisms by which mathematical sciences technology is transferred to users are weak. This adversely affects the culture of innovation in Australia. Thus it is important that existing mechanisms be exploited, existing highlights acknowledged and new mechanisms entertained.

**Recommendation 6a**

- ☐ Academic mathematical scientists are encouraged to bid more vigorously for ARC Collaborative Research Awards and Australian Postgraduate Awards (Industry).

[**Mathematical scientists**]

**Recommendation 6b**

- ☐ The Mathematics-in-Industry Study Group should be continued, preferably as part of the activities of a CRC for Industrial Applications of the Mathematical Sciences. Should such a CRC not be established, then the Australian Mathematical Society (through ANZIAM) is encouraged to co-ordinate ongoing arrangements for the Study Group.

[**Chief Scientist, ANZIAM**]

**Recommendation 6c**

- ☐ Mathematical scientists are encouraged to communicate more effectively with the media and general public.

[**Mathematical scientists**]

**Recommendation 6d**

- ☐ CSIRO is encouraged to continue its funding support for the activities of CSIRO Division of Mathematics and Statistics. This Division should continue to operate on a disciplinary basis.

[**CSIRO**]

**Recommendation 6e**

- ☐ DIST is encouraged to develop a specialist program so that small to medium enterprises (SMEs) have access to advanced mathematical services. The benefits of this program should be communicated. SMEs need to be assured of access to the 150% taxation benefit for advanced mathematical services provided to them.

[**DIST**]

**Recommendation 6f**

- ☐ Academics are encouraged to seek secondments to industry during periods of study leave. Where payments are made by industry for these secondments, taxation relief should be available to the employers.

[**Mathematical sciences researchers, ATO**]

Australian mathematics is greying. The age distribution of staff in mathematical sciences departments is heavily skewed towards the 45 and upwards group. If retirement continues to take place by age 65 as at present, there will be a large number of retirements over the 10–15 year scope of this review. Alternatively, if non-compulsory retirement becomes the norm across Australia, then the number of retirements is likely to be less, but replenishment of the profession by young researchers will be diminished. In either case, the profession faces a major challenge because of the present age structure of departments.

**Recommendation 7**

- ☐ Universities must develop plans to address difficulties caused by the present age structure in mathematical sciences departments. Consideration should be given to attractive early retirement plans and mechanisms for retaining promising postdoctoral researchers and grooming future leaders in the profession.

[**AVCC, Deans, Heads of Department**]

The mathematical sciences in Australia, as in most parts of the world, suffer from a chronic gender imbalance at senior levels. It is important to encourage talented female students to continue in the profession. The review found that talented female students need different sorts of support at different stages of their career: on entering university, after an undergraduate degree, and then as a postdoctoral researcher or junior academic.

**Recommendation 8a**

- ☐ Professional societies, academic departments and employers of mathematical sciences graduates are encouraged to promote activities, aimed at senior high school students and senior undergraduates, which demonstrate career opportunities for talented female mathematical sciences students and which encourage them to continue to further studies.

[**Heads of Department, Professional Societies**]

**Recommendation 8b**

- ☐ The ARC is encouraged to award a special two year postdoctoral award to provide a role model for female mathematical scientists. The award, which would need to be appropriately publicised, might be called the Hanna Neumann Postdoctoral Fellowship.

[**ARC**]

**Recommendation 8c**

- ☐ Employers are encouraged to provide flexible arrangements so that female researchers at postdoctoral or junior academic level can continue their careers after breaks for child-rearing.

[**ARC, AVCC**]

The mobility of mathematical sciences researchers between institutions is low by international standards, even allowing for the fact that Australia is a large, sparsely populated country. Greater mobility of researchers between institutions will improve the skills base and knowledge in the profession. We urge the introduction of mechanisms to improve the mobility of junior researchers.

**Recommendation 9a**

- ☐ Financial disincentives to mobility between institutions of postgraduates and postdoctoral fellows should be removed by provision of increased removal and travel allowances, and in other ways to be identified. Mathematical sciences departments should actively recruit postgraduates and postdoctoral fellows from other institutions.

[**ARC, Heads of Department**]

**Recommendation 9b**

- ☐ The professional societies are encouraged to facilitate access to information from university departments concerning possible PhD topics and supervision arrangements. Departments are encouraged to maintain such information on their World Wide Web pages, and the societies through their own WWW server should provide easy links to those pages and should publicise that fact.

[**Professional Societies, Heads of Department**]

There is a low awareness in industry of the contribution of the mathematical sciences to the economic competitiveness of the nation. In part, this results from the fact that mathematical sciences students do not have sufficient education and training in important skills such as communication, project work on industrial case studies, and collaboration in teams. We consider that a postgraduate diploma or master's level course is required to acquire these skills. Moreover, the act of talking to prospective employers and students will generate increased awareness.

**Recommendation 10**

- ☐ Departments are encouraged to carry out market research aimed at establishing master's level courses which will meet the needs of Australian industry. These courses should embody necessary mathematical, statistical and computational knowledge, communication skills, management methods, industrial placements and project work. As appropriate, these courses should be established.

[**AVCC, Deans, Heads of Department**]

The mathematical sciences now depend critically on computers for research and communication with colleagues. Moreover the mathematical sciences have become laboratory based; as such, funding for mathematical sciences departments should be on a comparable basis to computer science departments.

**Recommendation 11**

- ☐ Departments and universities should ensure that staff and students have access to appropriate computers, software, support staff and network connections. To support such infrastructure for advanced teaching, research and communications, mathematical sciences departments should be funded on a comparable basis to computer science departments.

[**DEET, AVCC, Deans**]

Developments in information technology will have a profound effect on the dissemination of knowledge in all disciplines, including the mathematical sciences. Within the time horizon of this review, journal publishing is almost certain to become largely electronic in nature. In addition, electronic developments like the World Wide Web will enable departments to promote their activities, increase the effectiveness of their teaching, and disseminate knowledge created by staff. It is impossible to be precise about details of the changes to be created by information technology developments, but it is possible to develop a mindset that will enable the changes to be relatively smooth and productive.

**Recommendation 12a**

- ☐ It is of utmost importance that networks be capable of handling the future challenges of the information age.

**[AVCC]**

**Recommendation 12b**

- ☐ Professional societies in the mathematical sciences are encouraged to continue their development of electronic operations. Mathematical sciences departments are encouraged to use the World Wide Web and its successors to promote their activities, to disseminate knowledge, and to increase the effectiveness of their teaching and research. Funding bodies such as the ARC are encouraged to provide funding to build up appropriate information technology infrastructure.

**[ARC, Professional Societies, Heads of Department, Deans]**

Hardware and software developments mean that the mathematical sciences have become laboratory based, and that computational science has become a third strand of scientific endeavour along with theory and experiment. Computer developments will have major ramifications on the way that the mathematical sciences are taught: for example, symbolic manipulation packages reduce the need for human involvement in algebraic manipulations, and packages enable routine solution of sets of ordinary differential equations. It is highly likely that further major changes to courses will take place over the 10–15 year horizon of this review.

**Recommendation 13**

- ☐ Mathematical sciences departments are urged to survey their courses and re-design them to make best use of the growing power of computers.

**[Heads of Department, Deans]**

As noted above, we see that computer developments will have a profound effect on the way that university mathematics is taught in the future. A ‘universal acquisition’ policy will help departments cater for future needs of students in an efficient way.

**Recommendation 14**

☐ The government is encouraged to introduce a funding scheme (*e.g.* of HECS type or by way of low cost loans, and/or by sales tax exemption) by which all mathematical sciences students can readily acquire a suitable computer, software and modem connections. Universities and departments should support this recommendation by providing appropriate software and network connections, and by using bulk-buying power to obtain low prices for hardware and software.

[**DEET, AVCC, Deans, Heads of Department**]

The mathematical sciences have a major effect on multi-disciplinary research and on the economic competitiveness of Australia. Nevertheless it is sometimes difficult to ascertain just how far the mathematical sciences have penetrated into industry and other fields. In this context, we make the following two recommendations which will assist policy formulation.

**Recommendation 15**

☐ The Department of Industry, Science and Technology should introduce Field of Research classifications into applications for the 150% tax concession for industrial Research and Development.

[**DIST**]

**Recommendation 16**

☐ The Australian Mathematical Society is encouraged to collaborate with the other professional societies to maintain

- a register of ARC Large Grants awarded for mathematical sciences research
- a register of PhD students in the mathematical sciences with information including topic, supervisor, funding support, gender

[**Australian Mathematical Society**]

The funding base for research in the mathematical sciences is relatively narrow. It consists primarily of ARC grants and funds generated by service teaching. Although the mathematical sciences community has been successful in winning an appropriate share of ARC funds, the profession would benefit by broadening the funding base for research.

**Recommendation 17**

☐ To broaden the funding base for the profession, mathematical sciences researchers are encouraged to apply for funds from a wide range of sources including

- ARC collaborative grants scheme
- APA (Industry) collaborative grants scheme
- the ARC Key Centres program
- competitive research grants from the Industry R&D Board of DIST
- the DIST Bilateral Science and Technology Program (for international collaboration)
- industry association funds
- other government programs including NHMRC funds

[**Academic researchers, Heads of Department, Deans**]

Service teaching is a very important activity for mathematical sciences departments. It contributes to the development of inter-disciplinary collaboration and provides funds to maintain the department and its research programs.

**Recommendation 18**

☐ Departments must recognise the role that service teaching plays in maintaining the mathematical level of other disciplines and fostering links with those disciplines. Departments should be attentive to nurturing service teaching arrangements and meeting the needs of client disciplines. Universities should beware of fragmenting the mathematical sciences through devolution of service teaching.

[**Heads of Department, Deans, AVCC**]

Australia has a need for a special research centre to enrich basic research in the mathematical sciences and thereby contribute to the framework on which applied research can be built. To provide the flexibility to address changing needs, particularly rapidly developing opportunities, this Centre should have no permanent scientific staff, and should rely on visiting scholars to undertake research programs.

**Recommendation 19a**

☐ The Australian Research Council should facilitate application under the SRC program by the mathematical sciences disciplines for a National Research Centre in the mathematical sciences.

**Recommendation 19b**

- ☐ The National Committee for Mathematics should conduct a competitive tender amongst universities prepared to offer funds to be the site of a proposed National Research Centre in the mathematical sciences in similar style to MSRI, IMA, the Fields Institute or the Newton Institute.

[**ARC, National Committee for Mathematics**]

In contrast with many disciplines, the mathematical sciences do not possess a specific industry sector which can provide funding and industrial collaboration. Consequently, there are structural difficulties in establishing high level collaborative activities and in winning major grants such as those for Collaborative Research Centres. Nevertheless, the evidence is compelling that the mathematical sciences are pervasive throughout industry and essential to the economic competitiveness of the nation. It is important to strengthen the mechanisms by which mathematical sciences technology is developed and transferred to users. We believe this will help to develop a culture of innovation in Australia. The CRC program offers a way to achieve these goals.

**Recommendation 20**

- ☐ The government should identify the mathematical sciences as an under-represented discipline in the CRC program and should therefore invite proposals to establish a CRC for Industrial Applications of the Mathematical Sciences.

[**DPMC, Chief Scientist**]

# 1

# The Mathematical Sciences in Australia

The aim of this chapter is to set the scene for the entire review by introducing key issues and placing them in broad context. We look at the classification of research in the mathematical sciences, and then characterise mathematical sciences research in the nation's universities, government laboratories and private sector. We also list the key attributes of the Australian professional associations for the mathematical sciences.

## 1.1 Classifications

In the Executive Summary, we describe the mathematical sciences in a way that goes beyond standard dictionary definitions such as

*mathematics*: *the science that treats of the measurement, properties and relations of quantities* (Macquarie Dictionary)

*mathematics*: *science of number, quantity, shape and space* (Collins Gem Dictionary)

Most professional mathematicians would feel uncomfortable with those definitions; they do not capture the complexity, diversity and richness of the mathematical sciences. The situation is not helped by a simplistic classification that has existed for much of the present century, namely that mathematics consists of three strands: pure, applied and statistics. In Australia, pure mathematics was typified by analysis, algebra, geometry; applied mathematics by fluid and solid mechanics (and, more recently, numerical analysis); and statistics by data analysis and probability. The present Field of Research classification of the Australian Standard Research Classification still uses these terms, and uses them to describe a number of sub-fields as listed in Table 1.1.

The descriptors 'pure' and 'applied' imply a sharp demarcation that is illusory. Nowadays, branches of mathematics that were developed out of abstract and aesthetic reasons have everyday applications of immense practical importance (see Box 1.1), the mathematical sciences are deployed routinely in collaborative research, and the edges have been blurred between the mathematical sciences and disciplines like computer science, engineering and economics. Nevertheless, the old classification persists, even to the extent of naming and conditioning the operation of departments at some major universities. The old classification is an inadequate way to represent the profession to students and academic colleagues.

Table 1.1: Australian Standard Research Classification of the mathematical sciences by Field of Research

| pure mathematics | applied mathematics | statistics |
|---|---|---|
| math logic, set theory number theory, group theory | numerical analysis, theory of computation, analysis of algorithms | probability theory |
| algebraic structures | differential equations, integral equations | stochastic modelling and analysis |
| approx theory, Fourier analysis, harmonic analysis, pot'l theory | optimisation, control theory | statistical theory |
| functional theory | classical mechanics, fluids, optics, electromagnetism | applied statistics |
| operator theory | applied math (other) | statistics (other) |
| geometry, topology | | |
| pure math (other) | | |

We prefer to speak of the 'mathematical sciences' which encompass the full range of mathematical research and its applications. The phrase includes mathematics in its own right, various applications of mathematics, statistics, operations research, actuarial science and computational mathematics. Research in the mathematical sciences needs to be more comprehensively classified than by the old descriptors: 'pure', 'applied' and 'statistics'. Our first recommendation is one of classification:

**Recommendation 1**

- ☐ In addition to the Field of Research classification, research activities in the mathematical sciences should be described by the Australian Standard Research (Type of Activity) Classification, namely basic research (pure or strategic), applied research and experimental development.

[Recommendation directed to: **Mathematical sciences researchers, Heads of Department, Deans**][3]

[3] The Australian Standard Research Classifications are defined by:

Pure Basic Research: experimental and theoretical work undertaken to acquire new knowledge without looking for long term benefits other than the advancement of knowledge.

In making this recommendation, we are aware that this classification too is imprecise; it will sometimes be difficult to distinguish between pure basic and strategic basic research. Overall, however, we believe that the Type of Activity Classification gives an additional valuable way to describe the activities of researchers.

Where possible, we see benefits in gathering researchers of kindred spirits together in mathematical sciences schools. In some universities (*e.g.* Macquarie University and the Australian National University), a statistics department exists in a different faculty to the rest of the mathematical scientists. We see this as undesirable because it leads to duplication of facilities and organisational structures. It also reduces the chances of beneficial interaction between various branches of the mathematical sciences.

**Box 1.1 Cryptomathematics**

Various branches of mathematics are used to develop new methods of encryption and decryption. In addition to obvious applications in intelligence agencies, there are applications to transmission of confidential data in industry and business. A whole field of mathematics — cryptomathematics — has developed.

Mathematical topics required for cryptography include algebra (especially linear algebra, finite fields), probability theory (especially stochastic processes and markov chains), computer science (design, implementation and evaluation of algorithms), number theory, statistics (in particular 'small sample' statistics), discrete optimisation, combinatorics, harmonic analysis, information theory and data analysis.

Within Australia's defence establishments, approximately 50 people carry out cryptomathematical research and pursue its applications. The importance of the field is captured in the remarks 'we regard them [cryptomathematical researchers] as our most important resource' and 'the national security depends on cryptomathematical advice'.

[Transcript of interview with Mr Martin Brady, Director, Defence Signals Directorate]

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Strategic Basic Research: experimental and theoretical work undertaken to acquire new knowledge directed into specific broad areas in the expectation of useful discoveries. It provides the broad base of knowledge necessary for the solution of recognised practical problems.

Applied Research: original work undertaken primarily to acquire new knowledge with a specific application in view. It is undertaken either to determine possible uses for the findings of basic research or to determine new ways of achieving some specific and predetermined objectives.

Experimental Development: systematic work, using existing knowledge gained from research or practical experience, that is directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed.

## 1.2 Mathematical Sciences in the Universities

The preponderance of basic research in the mathematical sciences in Australia resides in universities. The Administrative Directory of Mathematical Sciences in Australasia published by the Australian Mathematical Society in 1994 lists 1024 staff members in 62 departments in 35 universities.

Since the number of departments and researchers is large and most departments have representation in many sub-divisions of the Field of Research classification (Table 1.1), we have not constructed a taxonomy of mathematical sciences departments in Australia. We do however identify areas of strength in Chapter 2. In fact, however, the mathematical sciences are much more pervasive than is suggested by Table 1.1. This point is examined below and in Chapter 2.

There is an obvious dichotomy between universities established before 1980 and those established after 1987 when, as part of a reform of higher education in Australia, colleges of advanced education and institutes of technology became universities. Typically, the older universities have bigger mathematics departments, conduct more research and supervise more postgraduate students. The more recent universities face a challenge to develop research activities whilst maintaining their commitment to teaching. Illustrative profiles are given in Box 1.2. Within this dichotomy, there is also a wide size range for departments, from small (*e.g.* James Cook University, 13 staff in its Department of Mathematics and Statistics) to large (*e.g.* University of NSW, 88 staff in the School of Mathematics).

The main sources of funds for university mathematical sciences departments are block grants for teaching and research from their universities and ARC large grants. The university allocation is usually a weighted multiple of Equivalent Full Time Student Units (EFTSU) taught, and ARC small grants. Special ARC infrastructural grants were made available to the new universities to assist in establishing research activity. Service teaching brings valuable EFTSUs to mathematics departments. Not all academic time is allocated to teaching, and it is widely assumed that something like one third of an academic's time is available for research. Submissions to the review showed significant variation in this figure; plainly the assumption for accounting purposes that one third of an academic's time is dedicated to research should be treated with caution. A frequent comment in submissions was that 'there is just not enough time for research'.

**Box 1.2 Illustrative departmental profiles: established versus new universities**

There is little point in trying to define a typical Australian mathematical sciences department. Instead we describe two departments which characterise aspects of established and new universities.

The Department of Mathematics at the University of Western Australia seeks to "be competitive with the best mathematics departments worldwide in terms of research and scholarship, and to provide the highest quality of teaching of mathematics". This excellence is achieved in a number of sub-divisions of the Field of Research classification. The full time academic staff consists of 27 males and 2 females. Only 6 full time staff members are under 40, and the Department is viewed as somewhat oversized. There are currently 21 full time PhD students and the Department expects 29 full time PhD students in 2004 (or 1.5 postgraduates per staff member). The Department has major research strengths in combinatorics, finite geometry, dynamics and topology, rings and semigroups, pattern recognition, applied and pure probability, stochastic modelling, optimisation and control, fluids and continua [list abbreviated for reasons of space]. Since 1989, the Department has produced 612 papers, articles and monographs. In 1994, the Department was a participant in 10 grants (mostly ARC) over $20,000.

The Swinburne University of Technology Act was proclaimed in 1992, completing the change of the former Swinburne Technical College established in 1909 to a University. The School of Mathematical Sciences at Swinburne has a full time academic staff of 17 males and 4 females, 10 over 50 years old and none younger than 36. There are 3.6 equivalent full time support staff. The School sees significant constraints to its research plans because of high teaching loads, lack of high quality students from undergraduate programs, lack of research infrastructure, and very little research tradition. No staff member has held an ARC Large Grant, nor has the School awarded a PhD to date. Nevertheless, the School is pushing ahead with plans for research; it now has 6 full time PhD students, and anticipates having 12 full time PhD students in 2004. The research that is under way is very applied in nature, for example, mathematical and computational modelling of oil spills.

University departments naturally have other sources of funds: NHMRC funds are awarded to statistical researchers, there are collaborative grants with CRCs and other government agencies, and there is sponsored and contract research. Some universities have set up consulting groups, often statistical in nature. A good example here is the Statistical Consulting Centre at the University of Melbourne which now employs four people full time and three part time on externally-generated funds.

Overall, however, it is clear that the principal source of funds for mathematical sciences research in universities comes as part of the teaching allocation and from ARC funds. The funding base for academic mathematical sciences research needs to be broadened. We discuss this matter in detail in Chapter 7.

The principal output of academic research in the mathematical sciences is papers in learned journals and in conference proceedings; perhaps one might add lines of programming code to that output. As explained later (Chapter 5), there is also a steady production of PhD graduates ready to join the research workforce.

Overall impressions of the vigour and impact of mathematical sciences research in Australia can be gleaned from Figures 1.1 and 1.2 which show, respectively, publication performance by discipline and publication performance ranked by impact. During the 12 year period to 1992, Australia published 2.3% of the world's papers in mathematics, and these papers were cited 10% more than the average for mathematical sciences papers worldwide. Incidentally, for many years the Science Citation Index failed to include major Australian mathematical sciences journals; that failure extends to the compilations alluded to below. Given a natural tendency for Australians to dominate in Australian journals, the citation indices probably underrate the Australian impact. Comparisons with other disciplines are obvious from the figures. This is convincing evidence of a healthy research base in the mathematical sciences in Australia. Further discussion on funding trends, from which inferences can be drawn about outputs, are given in Chapter 7.

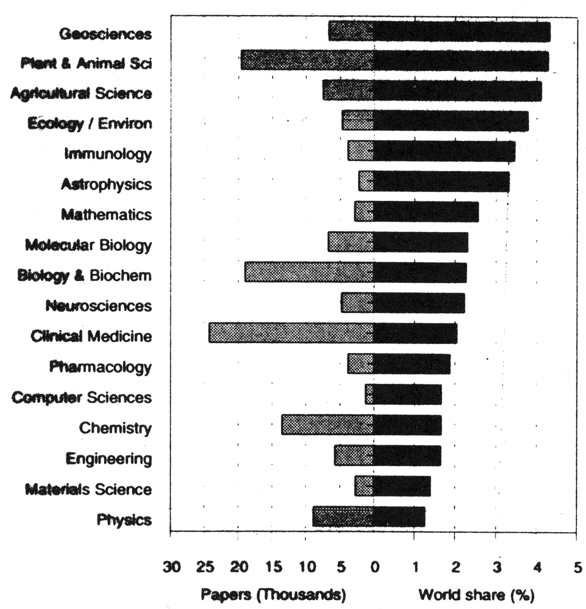


Figure 1.1: Australian publication performance by research discipline. [Australian Science and Technology, 1994, fig. 36]

Figures 1.1 and 1.2 however convey an incomplete picture because much research in the mathematical sciences is based on collaborations with other disciplines. Moreover, a significant amount of research in other disciplines is mathematical in nature. This pervasiveness of the mathematical sciences can be overlooked but is readily explainable once we examine the reality: whatever the discipline, one builds models, almost invariably quantitative models — which by definition call on the mathematical sciences — and these contribute enormously to one's understanding of the physical phenomenon or abstract system. In this and other ways the mathematical sciences make a valuable contribution to the work of other disciplines.

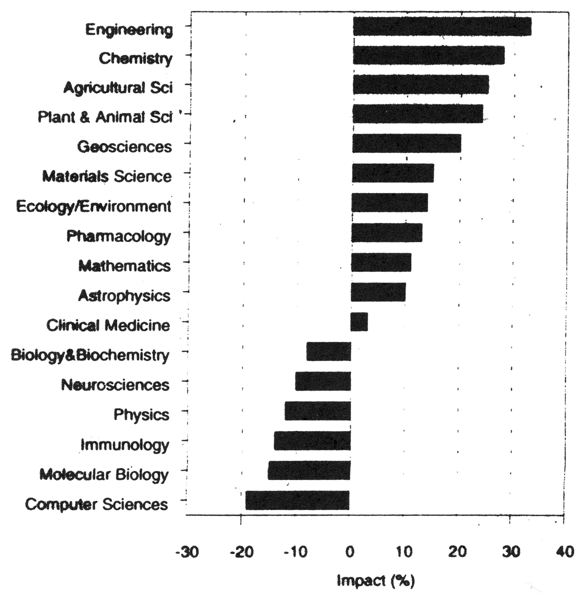


Figure 1.2: Publication performance for various disciplines ranked by impact.
[Australian Science and Technology, 1994, fig. 37]

Table 1.2: Assignment of journal publications from Australian university departments to SCI fields of research 1981-1990; figures in percentages.

| | Fields of Research | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Depts | Math | Phys | Chem | Earth | Infm | Appl | Eng | Biol | Agric | Med | Multi |
| Math | **48** | 30 | 4 | 5 | 3 | 1 | 8 | 6 | 1 | 3 | 3 |
| Phys | 0 | **76** | 4 | 9 | 1 | 3 | 3 | 2 | 0 | 3 | 9 |
| Chem | 0 | 13 | **72** | 6 | 0 | 1 | 2 | 6 | 1 | 2 | 7 |
| Earth | 1 | 2 | 3 | **78** | 0 | 0 | 3 | 9 | 1 | 1 | 10 |
| Infm | 17 | 15 | 1 | 1 | **53** | 1 | 31 | 3 | 2 | 3 | 5 |
| Appl | 0 | 12 | 23 | 4 | 0 | **22** | 10 | 20 | 13 | 3 | 12 |
| Eng | 3 | 17 | 4 | 11 | 8 | 11 | **53** | 6 | 1 | 2 | 15 |
| Biol | 0 | 4 | 1 | 4 | 0 | 0 | 0 | **69** | 3 | 24 | 7 |
| Agric | 0 | 1 | 1 | 2 | 0 | 2 | 0 | 35 | **54** | 16 | 2 |
| Med | 0 | 3 | 2 | 0 | 0 | 0 | 0 | 15 | 1 | **81** | 6 |

[P Bourke & L Butler "Mapping scientific research in universities" (ANU, 1993)]

The pervasiveness of the mathematical sciences compared to other disciplines is illustrated in Table 1.2, which shows how papers from various Australian university departments are published in journals categorised in fields belonging to other disciplines. The data covers the period 1981-1990. The table shows that there is about a 25% 'spill' of activities from chemistry, earth sciences and physics departments to other disciplines. In contrast, *more than 50% of the research output of mathematics departments appears in the journals of other fields, notably physics and engineering.*

**Box 1.3 International connections**

During its site visits, the Working Party received many comments emphasising the importance of international connections for the mathematical sciences in Australia. Many senior academics regarded provision for international travel as an indispensable part of grant applications.

To explore the importance of international visitors, we distributed a secondary survey asking departments to list the number of international visitors and the benefits to them of such visits. The response was overwhelming: 26 departments immediately sent in detailed responses, often many pages in length. As typical responses, the University of Tasmania had 28 international visitors in 1994; the Mathematics Department at Macquarie University brought to Australia and supported 24 medium or long term visitors in 1993; and the combined number of visitors during 1994 to the Departments of Mathematics and Statistics at the University of Melbourne was 42, many of whom stayed for long periods. The University of Melbourne identified some 15 large scale and long term collaborative research projects with international co-workers.

The submission by Swinburne University of Technology identified the benefits as:

- keeping abreast of latest techniques
- providing the opportunity for academic mathematical discussions and research discussions in a variety of interest areas
- allowing discussions on quality/best practice processes at other universities
- the development of an international network of people with interests in similar fields
- providing critical evaluation and discussions with graduate students

The whole issue was neatly summed up in the submission from La Trobe University's Department of Mathematics: "It should be clear that visits from overseas academics are of immense benefit to this department."

One further point needs to be made in this introductory section, namely the strength of international contacts of mathematical sciences departments. As part of the review, academic departments were surveyed to ascertain how many international visitors had been hosted in the recent past and how these visitors had contributed to research under way in Australia. The strength of the replies is typified by the responses shown in Box 1.3. Without doubt, Australian-based researchers in the mathematical sciences are very well-connected with international colleagues, and these connections have a major impact on work under way in Australia. Modern information technology developments, particularly e-mail, strengthen the connections.

Thus Australia has an internationally reputable basic research infrastructure in the mathematical sciences. But, with only about 2% of the world's research in the discipline, we rely on international connections to assist much of the research development in Australia. The indications are that these international connections and influences are growing stronger.

## 1.3 Mathematical Sciences in Government Laboratories

Most university research in Australia in the mathematical sciences lies in the category of basic research. In government laboratories, however, the emphasis is on applied research and experimental development.

The largest groups of mathematical sciences researchers in government laboratories occur in CSIRO Division of Mathematics and Statistics, the Australian Bureau of Statistics, and the Defence Science Technology Organisation. (Telecom [Telstra] Research Laboratories also have a notable presence, but they are classified under industrial groups – see Section 1.4.) These large government groups are discussed in more detail in Chapter 3 under advanced mathematical services.

Many other government laboratories in Australia, both federal and state, employ mathematical sciences PhDs. Examples include other CSIRO Divisions, the Bureau of Meteorology, and various primary industry departments that employ biometricians. Here is a submission describing the importance of the mathematical sciences:

> In this Centre we do not see mathematics as a 'service' but as an integral part of the research process. Scientists are expected to develop the mathematics required to follow out the implications of their analysis of physical phenomena. This work generally concentrates on the following areas: solution of PDEs [partial differential equations], especially

> variants of the Fokker-Plank equation and the Reynolds equations; solution of ODEs [ordinary differential equations]; differential geometry; numerical methods; time series; classical mathematical physics.
>
> [Dr John Finnigan, Head, CSIRO Centre for Environmental Mechanics]

The pervasiveness of mathematics is also evident in activities of various Cooperative Research Centres established in Australia in recent years. In a submission from the CRC for Aerospace Structures (CRC–AS), we read that

> It is anticipated that cost reductions in computer software and hardware will enable advanced modelling and simulation capabilities to be applied to most design and manufacturing problems. Modern aerospace vehicles cannot be cost or performance competitive without advanced computer methods being used in their design. Advanced finite element methods [a branch of computational mathematics] have been used by the CRC–AS over the past 3 years to research new design concepts.

This quotation illustrates the blurring of the interface between the mathematical sciences and engineering. The advanced finite element methods mentioned require an elaborate mathematical infrastructure which has been built up over many years. To the engineering user, however, these concepts are now readily available in user-friendly software packages.

Despite the pervasiveness of the mathematical sciences in the CRC program and in industry, it is notable that no CRC exists to carry out strategic basic research and applied research in the mathematical sciences. A key recommendation of this review, discussed in detail in Chapter 8, is the establishment of a CRC for Industrial Applications of the Mathematical Sciences.

Funding for the mathematical sciences in government laboratories comes from many different sources. Experimental development is generally funded by the user — either by contract or by mathematical scientists working in various government departments. The large laboratories mentioned above also have appropriation funds for applied research and some strategic basic research. A limited amount of funding comes from competitive government grants (sponsored through DIST) and funds from granting bodies associated with particular industry sectors in Australia.

## 1.4 Mathematical Sciences in the Private Sector

Business expenditure in Research and Development in Australia is low by international standards. Figures for expenditure on R&D as a percentage of Gross Domestic Product (GDP) appear in Table 1.3.

In recent times, the amount of industrial R&D in Australia has maintained a good growth rate. The latest figures (1994-95) show that the gross expenditure on R&D is more than 1.5% of GDP. This does not however have a significant effect on the nation's ranking in Table 1.3.

Thus industrial applications of the mathematical sciences in Australia, which usually fall in the category of experimental development, are still only about one half of the levels (as a % of GDP) of countries like USA, France, Germany and the UK. Anecdotal evidence supports this hypothesis. We conclude that industrial application of the mathematical sciences in Australia is neither broad nor deep by the standards of best international practice.

There are, of course, some instances where the mathematical sciences are very effectively applied in Australian enterprises. A handful of large businesses – like BHP, Telstra (Telecom as was), and various banks and investment houses – employ many mathematicians. There are also isolated mathematical scientists employed in a diversity of companies. As would be expected in the Australian economy with its emphasis on minerals, the Working Party encountered small groups of mathematical scientists working in mineral exploration and mineral processing.

The Working Party received submissions from a handful of companies that have a consulting role based on use of the mathematical sciences. Most of these small enterprises were based on statistical work that converts data into information and the design of data collection systems. A few, such as OPCOM (see Box 1.4) are based on the use of operations research.[4] The Working Party believes it would be healthy if more of these consulting and software companies could be spun off from academic departments. This point is examined again in Chapter 3.

[4] Operations research is a sub-field of the mathematical sciences which is concerned with the optimal allocation of scarce resources – human, financial, physical – to best meet competing demands. The field was established in World War II to provide a rational deployment of matériel for military purposes. It is interesting to note that several large Australian companies had operations research departments 20 years ago. All these departments have now gone, and the practitioners dispersed to other parts of the companies.

Table 1.3: Source of R&D funds as a % of GDP.

| country | gross | business | government |
|---|---|---|---|
| **Large R&D performers** | | | |
| Japan (1991) | 2.87 | 2.22 | 0.47 |
| USA (1991) | 2.75 | 1.39 | 1.29 |
| Germany (1991) | 2.66 | 1.61 | 0.97 |
| France (1991) | 2.42 | 1.03 | 1.18 |
| UK (1991) | 2.08 | 1.04 | 0.71 |
| China (1990) | 0.72 | 0.29 | 0.43 |
| **Medium R&D performers** | | | |
| Sweden (1991) | 2.90 | 1.75 | 1.11 |
| Switzerland (1989) | 2.86 | 2.13 | 0.65 |
| Netherlands (1991) | 1.91 | 0.98 | 0.86 |
| South Korea (1990) | 1.86 | 1.56 | 0.30 |
| Chinese Taipei (1990) | 1.69 | 0.88 | 0.78 |
| Belgium (1990) | 1.69 | 0.88 | 0.47 |
| Canada (1991) | 1.50 | 0.62 | 0.66 |
| **AUSTRALIA (1990-91)** | **1.34** | **0.53** | **0.74** |
| Italy (1991) | 1.32 | 0.63 | 0.62 |
| Spain (1991) | 0.87 | 0.40 | 0.38 |
| India (1990) | 0.79 | 0.18 | 0.61 |
| **Small R&D performers** | | | |
| Finland (1991) | 2.02 | 1.14 | 0.83 |
| Norway (1991) | 1.84 | 0.82 | 0.91 |
| Denmark (1991) | 1.69 | 0.87 | 0.67 |
| Austria (1991) | 1.51 | 0.76 | 0.70 |
| Ireland (1991) | 1.04 | 0.54 | 0.28 |
| Iceland (1991) | 1.01 | 0.24 | 0.66 |
| Singapore (1990) | 0.90 | 0.49 | 0.41 |
| New Zealand (1990) | 0.88 | 0.29 | 0.57 |
| Portugal (1990) | 0.61 | 0.17 | 0.38 |
| Turkey (1990) | 0.47 | 0.13 | 0.33 |
| Greece (1991) | 0.46 | 0.10 | 0.27 |

[Australian Science and Innovation Resources Brief, 1994, DIST]

**Box 1.4 Profile of OPCOM**

OPCOM was founded in 1985 by two academics from the Department of Mathematics at the University of Queensland. It has grown to a successful operations research and systems development company, now employing 12 people. Software systems are provided for vehicle routing and scheduling, crew scheduling, rostering, timetabling, simulation and modelling, *etc.* Their client list is mainly Brisbane–based and covers a wide range of industry sectors. In his submission to the review, Dr Holt, one of the founders of OPCOM, said “without high level mathematics, OPCOM could not function” and “mathematicians are excellent problem solvers”. Dr Holt noted that there are opportunities for mathematicians to establish small companies like OPCOM. In setting up such companies, key issues like recruitment difficulties and the essential need for expensive computer hardware and software in the company must be overcome.

## 1.5 Professional Associations for the Mathematical Sciences

The main professional associations for research–level mathematical scientists in Australia are:

*Australian Mathematical Society* (AustMS): founded in 1956; membership of 1100 (including 500 members in ANZIAM[5], its applied mathematics division); principal activities include publication of the *Journal of the Australian Mathematical Society*, Series A and B and conferences. ANZIAM has specialist interest groups in Computational Mathematics and Engineering Mathematics.

*Statistical Society of Australia Inc* (SSA): founded in 1947; membership of 910; principal activities include publication of *Australian Journal of Statistics* and *Newsletter* and conferences.

*Australian Society for Operations Research* (ASOR): founded in 1971; membership of 400; principal activities include a biennial conference and publication of *ASOR National Bulletin*.

*Combinatorial Mathematics Society of Australasia:* founded in 1978; membership of 130; principal activities include an annual conference and publication of *Australasian Journal of Combinatorics* and *Newsletter*.

*The Institute of Actuaries of Australia* founded in 1897; membership of 1633; principal activities include education of actuarial students, continuing professional education, submissions to Government and other bodies. The Institute of Actuaries is in fact a regulatory body in that members have to pass examinations and receive formal accreditation necessary for them to practise their profession.

One comment often heard in submissions to the review was that the public image of the mathematical sciences is poor.[6] (These comments are the basis of part of Finding 4.) This manifests itself in low public awareness of the pervasiveness, utility and beauty of the mathematical sciences. It means that it is difficult to attract enough good students to study the subject, and, overall, that it is hard to demonstrate the professional qualities of practitioners. It is gratifying to see, therefore,

[5] Australian and New Zealand Industrial and Applied Mathematics.

[6] For that matter, the public *understanding* of the mathematical sciences is arguably worse. See Section 2.1 for a discussion of levels of awareness of the mathematical sciences.

that both the Australian Mathematical Society and the Statistical Society of Australia are introducing accreditation for members. We see this as an important way of bolstering the public image of the profession.

Another group of professional associations is concerned with educational aspects of mathematics at various levels. This group includes the *Mathematics Education Lecturers Association* (MELA), the *Mathematics Education Research Group of Australasia* (MERGA), and the *Australian Association of Mathematics Teachers* (AAMT).

Five associations (AAMT, AustMS, MELA, MERGA, SSA) form the *Australian Mathematical Sciences Council* (AMSC) which has representation on the *Federation of Australian Scientific and Technological Societies* (FASTS), the peak lobby group for science and technology in Australia.

The mathematical sciences professional associations support conferences and have a strong publishing role. However, they are are neither large enough nor financially strong enough to provide in-depth services such as advertising, merchandising and preparation of major reports. This is merely a realistic reflection of economies of scale. Many mathematical scientists in Australia therefore choose to join appropriate overseas organisations which provide them with benefits not available in Australia. Two such organisations are the *American Mathematical Society* (AMS) and the *Society for Industrial and Applied Mathematics* (SIAM). These US organisations have many thousands of members and vigorous commercial activity (publishing, advertising, recruitment, merchandising) on a scale which seems impossible to attain in Australia. Throughout this report, we will make reference to influential reports published by these organisations.

# 2

# Basic Research in the Mathematical Sciences

This Chapter is concerned with pure basic and strategic basic research in the mathematical sciences in Australia (the footnote to Recommendation 1 contains definitions of these categories of research). In general, basic research in the mathematical sciences is confined to the university system. We describe the essence of this research, sketch its historical developments, make a snapshot of current activity, and look at the role of the Australian Research Council in sponsoring this research.

## 2.1 The Nature of the Mathematical Sciences

There are many levels of awareness of the mathematical sciences. Steen[7] formulates four levels of understanding — practical arithmetic, civic application, professional use and cultural appreciation. The first of these is the kind of applied arithmetic which assists in making decisions in one's personal life. Civic application implies public understanding of, for example, legislative issues which involve data with mathematical or statistical content, and being able to discriminate between rational and reckless claims in the technological arena. Professional use involves use of the mathematical sciences as a tool in the work place, and cultural appreciation is an understanding of the role of the mathematical sciences as a major intellectual achievement. Because the mathematical sciences are so universal, most educated persons can use them in the practical sense, but many have little awareness of the interdisciplinary benefits of the mathematical sciences, and few reach a level where they can appreciate the mathematical sciences as a supreme creation of the human intellect.

At the research level, the mathematical sciences are astonishingly diverse. A hundred years ago, it was possible for researchers to make contributions across the whole discipline, but this is now at best an astonishing exception. It also requires a long period of study to reach

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[7] L A Steen, "Literacy in mathematics" in R J Murnane & S A Raizen, *Improving indicators of the quality of science and mathematics education in grades K-12* (National Academy Press, Washington, DC, 1988), pp 20–22.

research level in specialisations of the discipline and to be eligible for an academic appointment: four years to earn an honours bachelors degree, at least three years for a PhD, and then several years postdoctoral research.

The mathematical sciences are often believed to be a field in which major research contributions are made relatively early in a career, say by the mid 30s. This generalisation has notable exceptions, however, and a significant minority of researchers maintain a prolific output deep into their professional lives.

The mathematical sciences are quite hierarchical in their intrinsic nature. Understanding depends on knowledge acquired at early stages of the long years of study forming the basis for later stages. Each stage of the education process is dependent on the output of the preceding stages. There is evidence that less time than previously is now devoted to mathematics in schools, and this is reflected in university students being less prepared for undergraduate study than in the past. There are complaints about the quality of students who pass upwards through the system, and these complaints are probably valid from the perspective of those who have previously passed through it. This is one manifestation of change in the mathematical sciences.

The mathematical sciences are a thoroughly international activity. The study of any particular area is virtually the same the world over. Most academic output in the mathematical sciences is subject to international peer review. Our practitioners in Australia speak the same mathematical language as do their colleagues overseas. It is essential for the health of the subject in Australia that we have regular and meaningful cross-fertilisation with overseas developments. This point was emphasised in Box 1.3.

The main requirements of individuals who wish to carry out research in the mathematical sciences are time for research, travel support to attend conferences and work with colleagues, library facilities, and, now, appropriate computing infrastructure.

For the mathematical sciences, as for many other disciplines, two key relationships warrant mention: that between teaching and research, and that between basic and applied research. Good researchers generally have an enthusiasm for their subject which shines through in their lectures and makes them attractive to students. Transmission of wisdom to students through supervision and teaching has long been recognised as a major activity for mature researchers. There are numerous examples of progress in the mathematical sciences motivated by practical questions which then sparked deep and creative theoretical investigations. Perhaps the most celebrated example is Newton's invention of calculus to solve astronomical problems, thereby promoting a mathematical development of enormous importance.

## 2.2 Development of Basic Research in the Mathematical Sciences in Australia

A review of the development of research in mathematical sciences in Australia enables us to place strategies for future research developments in context. Therefore we briefly describe significant features of progress since the 1950s. For further historical material, see Gani[8], MacDonald[9] and Potts[10]. Although this Section is primarily concerned with basic research, there has been an accompanying development of applied research as described by Braddock[11], Hurley[12] and Speed[13].

Prior to the 1960s, several distinguished mathematical scientists worked within the Australian University system and in the government sector. There was not, however, a strong culture of research development, and the strengths of Australian mathematics were generally the result of the presence of exceptional individuals for part of their career. Lamb (1874–81), Cherry (1929–63) and Pitman (1926–62) are examples. Box 2.1 highlights the career of Cherry. The only mathematical meetings occurred in the context of Section A of the annual ANZAAS conferences, and there was no journal devoted to the publication of mathematical research. No program of graduate education had been established and talented students were required to travel overseas to further their careers.

These various shortcomings were partially addressed by the formation of the Australian Mathematical Society and of the Statistical Society of Australia. Plans for the Mathematical Society were formulated in 1955;

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[8] J Gani, "Report on mathematics in Australian Universities", *Vestes* 7 (1964), 3–22.

[9] I D MacDonald, "Pure mathematics in the Australian universities", *Vestes* 11 (1968), 237–245.

[10] R B Potts (ed.) "Mathematical sciences in Australia 1981", *Australian Academy of Science* (1982).

[11] R D Braddock, "An anecdotal history of the Applied Mathematics Conference and the Division of Applied Mathematics", *Australian Mathematical Society* (1984).

[12] D G Hurley, "Mathematical research at the Aeronautical Research Laboratories 1939-1960", *J. Austral. Math. Soc. B* 30 (1989), 389–413.

[13] T P Speed, "The role of statisticians in CSIRO: past, present and future", *Austral. J. Statistics* 30 (1988), 15–34.

it was officially constituted in 1956 with a total of 123 foundation members. Contemporary lists indicate that this number encompassed approximately 70% of the research level Australian-based mathematicians. In 1956, the Mathematical Society held its inaugural Annual General Meeting at the University of Melbourne. This meeting was the precursor of the continuing series of midwinter conferences. The *Journal of the Australian Mathematical Society* was first published in 1959.

**Box 2.1 Professor T M Cherry**

T M Cherry was Professor of Mathematics at the University of Melbourne from 1929–63. He was an early President of the Australian Academy of Science and the foundation President of the Australian Mathematical Society. Cherry spent the early years of his research career in Cambridge, a pattern typical of many senior mathematics professors in Australia.

Cherry is best known for his work on asymptotic expansions and transonic flow during the late 1940s and 1950s. His most cited paper concerned asymptotic expansions for turning point problems. This work was published independently and contemporaneously with work by R E Langer, and it sparked interest which continued unabated for over 20 years, and, to a lesser extent, was still an active research area even 40 years later.

At the height of his career Cherry exerted considerable influence on the mathematical activities at the Aeronautical Research Laboratories which, in turn, influenced the research directions of many of the brightest applied mathematicians in Australia at the time (see Hurley, *op. cit.* for details). For further details of Cherry's career, see R Grimshaw, "An analysis of the impact of T M Cherry's work on asymptotic expansions", *J. Austral. Math. Soc.* B 30 (1989), 378-388.

After prolonged debate, the Society also founded an annual Summer Research Institute (SRI) as a residential summer school for active researchers. This Institute was modelled on the lines of a successful Canadian venture; its first meeting took place in Canberra in 1961.

In statistics, leadership was provided by the Statistical Society of NSW, which began publishing the *Australian Journal of Statistics* in 1959. The Statistical Society of Australia was formed out of the NSW association in 1962.

At the time of planning of the Mathematical Society, there was extensive discussion about the creation of a graduate school of mathematics in Melbourne, or in Sydney, as a focal point for graduates from other Australian Universities. Difficulties in obtaining adequate overseas scholarships for all deserving Australian mathematics graduates lent weight to this proposal but no consensus was reached. In addition, there were suggestions that an advanced postgraduate summer school would be preferential to the Canadian-style SRI. But these suggestions were defeated and graduate education in the mathematical sciences remained fragmented.

This situation was partially resolved by the creation, in 1963, of a Department of Mathematics in the Institute of Advanced Studies (IAS) at the Australian National University in Canberra and the appointment of B H Neumann as the Foundation Professor (see Box 2.2). The prime role of this department was graduate training and it rapidly developed an active doctoral program.

**Box 2.2 Professor B H Neumann**

Bernhard Neumann arrived in Australia in 1962 to become Head of the Department of Mathematics of the Institute of Advanced Studies at the Australian National University. Through his international standing and enthusiasm and intellect, he created an exciting environment for research and attracted many high quality mathematicians to Australia.

He established a very successful postgraduate program at the ANU and organised the first international conference in any field of mathematics ever held in Australia. He is a Fellow of the Royal Society, a former Vice-President of the Australian Academy of Science and President of the Australian Mathematical Society from 1964–66. Professor Neumann also played a major role in raising the international profile of mathematics in Australia through his work on the International Mathematical Union and with the Mathematical Olympiad.

For his lifelong achievements, Bernhard Neumann was appointed Companion of the Order of Australia in 1994.

Thus the period 1950–1965 witnessed the introduction of the basic infrastructure for mathematical research within Australia, the foundation of national associations, the organisation of regular conferences and research meetings, the publication of research journals, and the creation of a centre for graduate training.

The 1960s were a period of expansion and development for the Australian university system. The existing universities increased dramatically in size and new universities were created in major cities. This expansion, which was particularly strong in the scientific disciplines, created a great demand for suitably qualified staff. The Department of Mathematics in the IAS provided the largest source of Australian PhDs, generally with strengths in algebra and group theory. Other significant sources of PhDs were the Department of Statistics in the IAS under Professors Moran and Hannan, the Department of Mathematical Physics at the University of Adelaide under the leadership of Professors Hurst and Green, and the Department of Applied Mathematics at the University of NSW headed by Professor Blatt. Other departments and outstanding individuals also contributed. For example, Professors Mahler at ANU and Szekeres at Adelaide and then UNSW, had an important influence on the strength of Australian number theory. The expansion was also aided by the recruitment of young Australians trained overseas.

The rapid growth of Australian universities in the period 1965–1980 and the corresponding large recruitment has led to current demographic problems in the mathematical sciences (see Chapter 4). The present unbalanced age profile in academic departments arises from the substantial number of tenured appointments made in this period. Moreover the mathematical emphases of new departments were heavily influenced by the restricted number of sources of available appointees. This period also saw an expansion of the activities of the Australian Mathematical Society. In particular, a series of summer conferences in applied mathematics began in 1966 and a second journal devoted to applied mathematics was introduced in 1975.

The first major period of growth of the Australian university system ended by 1980, and, along with it, the expansion of mathematical sciences departments. The recruitment of tenured staff came abruptly to a halt. This had a number of consequences. A substantial number of highly qualified and well motivated mathematicians were frustrated in their ambition for mathematical careers in the universities and had to seek alternative employment. Others remained within the system moving from one fixed term position to another. The realisation that employment opportunities were rapidly decreasing had a dramatic effect on recruitment of mathematics students. Honours classes dwindled and graduate students disappeared (see Chapters 4–5 for more details).

Moreover, the early 1980s saw the beginning of a trend for students to avoid the sciences and to study for other professions and vocational disciplines. University employment policies led to the curious phenomenon whereby almost the only remaining permanent recruitment was at professorial level. Positions vacated at a lower level were either frozen or replaced by junior fixed term positions, but vacant chairs were usually re-advertised.[14] The late 1970s thus featured overseas recruitment of professors who introduced important new directions into Australian mathematics. There were also significant changes in research funding as described in Section 2.4.

The methods of mathematical research also changed in the 1980s, particularly in that international collaboration became much more prevalent. In earlier times, the main sources that were systematically used for visitors were the SRI of the Australian Mathematical Society and the visitors program of the Department of Mathematics in the IAS.

[14]Our anecdotal recollection is that in the decade there were just six tenured positions filled at subprofessorial level in pure mathematics in the total of the Australian universities.

The importance of regular contact with overseas experts with cognate interests seems only to be fully recognised in the last fifteen years. International collaboration grew rapidly in importance to the extent described in Box 1.3. An increasing supply of funds from the ARGS and its successor, the ARC, became available to assist these projects. In addition, the Centre for Mathematical Analysis at the ANU introduced a pattern of Special Years with funding for visitors dedicated to particular areas. These programs had substantial effects on the quality, quantity, variety and intensity of mathematical research in Australia. More recently, electronic communication has had an enormous impact by facilitating research at a distance.

Based on the membership of the professional societies (Section 1.5), we estimate there are now about 2,000 researchers carrying out some form of basic research in the mathematical sciences in Australia. This figure includes members of university departments, some employees of government laboratories, and postgraduate and postdoctoral students. Gani[15] estimated the corresponding number in 1963 to be 150. This corresponds to an annualised growth rate of 8.4% over 32 years. Note however that the number of people involved in what we term 'advanced mathematical services' is much larger. This point is examined in the next chapter.

## 2.3 Basic Research in the Mathematical Sciences (1995)

In this Section, we endeavour to give a picture of basic research in the mathematical sciences in Australia at present. This is no easy task, either to do or to comprehend, because of the diversity of work, the quantity and complexity of inter-disciplinary connections, the variety of institutions undertaking basic research in the mathematical sciences, and the number of researchers involved.

The output of basic research in the mathematical sciences consists mainly of publications. Bourke & Butler[16] have surveyed the publication output of Australian science for the period 1982-91, and we summarise their findings in Table 2.1. Before examining this table, note the following important points:

- Their data is from the Institute for Scientific Information which publishes the Science Citation Index (SCI). Their data includes journal publications in the form of articles, notes and reviews.

[15] op. cit., table 7.

[16] P Bourke & L Butler, "A crisis for Australian science", *Performance Indicators Project* (RSSS, Australian National University, 1994).

Papers in conference proceedings are sometimes but not invariably listed by SCI. The data is biased against Australian mathematics in that *inter alia* the SCI did not list *J. Austral. Math. Soc. (A)* during most of the period of the study.

- Their data is classified under various fields and sub-fields of science. The mathematical sciences are listed as a field with the following sub-fields: pure mathematics, applied mathematics, statistics and other mathematical sciences. We have already commented in Chapter 1 on the unsatisfactory nature of this classification.

- We have already commented on the penetration of the mathematical sciences into other disciplines; the Bourke & Butler study therefore could not capture a significant fraction of mathematical activity and output of mathematical sciences departments. Based on data for the Australian Research Council (see Tables 2.2a,b,c), we estimate that for this reason as much as 60-65% of mathematical sciences basic research activity is not captured in the Bourke & Butler study.

- The Bourke & Butler study uses 'fractionation' for collaborations; for example, assigning to each of four institutions collaborating in a paper one quarter of the paper.

- In the table, RCI denotes Relative Citation Impact = (share of citations)/(share of publications).

Note that Table 2.1 does not give as positive an impression as Figure 1.1 of Chapter 1 of Australia's publication effort in the mathematical sciences. In addition to the different time periods and treatment of fractionation, there is also the likelihood that different databases have been used by ISI.

According to Table 2.1, between 1982 and 1991 there was a slow decline in Australia's share of world publications in the mathematical sciences and almost no change in Australia's share of world citations. Thus the Relative Citation Impact of Australian publications in the mathematical sciences increased during the period. A high level of statistical research in Australia, with attendant high impact, is clearly evident. The sub-field 'other mathematical sciences' is a small sample in comparison with the three main sub-fields. Bourke & Butler also give convincing evidence of the increasing internationalisation of Australian science — *the percentage of Australian publications involving international collaboration almost doubled between 1981 and 1991.* Our anecdotal evidence suggests this trend may be stronger for the mathematical sciences in Australia than for Australian science overall. We stress again that, due to spillover to other disciplines, the data above probably only represents some 35-40% of basic research activity in the mathematical sciences in Australia.

Table 2.1: Citation results for the mathematical sciences, 1982–91.

| sub-field | Aust pubs (% of world) | % change (82/86–87/91) | Aust cites (% of world) | % change (82/86–87/91) | RCI | % change (82/86–87/91) |
|---|---|---|---|---|---|---|
| pure math | 1.12 | −23.77 | 1.20 | −21.87 | 1.08 | 18.57 |
| appld math | 1.76 | −5.33 | 1.76 | 7.00 | 1.00 | 2.50 |
| statistics | 3.07 | −17.29 | 3.37 | 13.12 | 1.10 | 13.03 |
| other math sci | 3.83 | −18.75 | 2.67 | 1.90 | 0.70 | 36.77 |
| total math sci | 1.67 | −16.01 | 1.97 | −0.42 | 1.18 | 25.42 |

We now describe specific areas of strength in basic research in the mathematical sciences in Australia. This challenging task was approached in several ways: by responses to questionnaires, by peer assessment, by direct observation by the Working Party, and by examination of Australian Research Council records. Another mechanism which was considered but not adopted was bibliometry. Our view is that the use of ARC records is the most useful way to identify areas of excellence.

The 1993 and 1994 Large Grants of the Australian Research Council were surveyed to identify grants that were either

1. classified directly as mathematical sciences[17], or

2. awarded to research teams with at least one member in a mathematical sciences department, but classified under other fields[18], or

3. awarded to researchers in non-mathematical sciences departments, but on topics that clearly have high mathematical science content[19]

[17]For 1993, such grants were defined to be those funded through the Physical and Mathematical Sciences Group in a specified mathematical category. For 1994, such grants were defined as those classified as mathematical sciences through their specified ABS Field of Research code, namely ABS code 010000 and sub-codes.

[18]*e.g.* "Propagation, interaction and stability of optical beams in nonlinear planar waveguides" which was awarded to R A Sammut and C Pask of the Department of Mathematics of the Australian Defence Force Academy.

[19]*e.g.* "Mathematical modelling of excitable tissues in the heart" which was awarded to B G Celler of the University of NSW under the Engineering and Applied Sciences section.

The results are presented in Tables 2.2a, 2.2b and 2.2c, thereby presenting a reasonably thorough picture of the diversity of basic mathematical sciences research in Australia and the extent to which it penetrates into other disciplines. Admittedly the Tables only contain data for two years, but the results are generally consistent with the observations of the Working Party about the areas of strength of basic research in the mathematical sciences in Australia.[20]

In view of the status and competitiveness of ARC funding, Tables 2.2a, 2.2b and 2.2c portray 'first league' research performance in the mathematical sciences. These grants include funding to support the direct costs of research, such as research assistants, computer hardware and software, travel and conferences.

Table 2.2a: 1993 ARC Large Grants classified directly under the mathematical sciences (classification 1 in the text).

| sub-topic | # of grants | $ |
|---|---|---|
| mathematical logic, set theory, lattices, etc. | 5 | 291,300 |
| number theory & field theory | 6 | 268,600 |
| rings & algebras | 1 | 57,600 |
| category theory, K theory homological algebra | 1 | 115,600 |
| group theory (including topological & Lie groups) | 5 | 190,600 |
| real & complex functions | 1 | 49,800 |
| differential, difference & integral equations | 8 | 418,200 |
| harmonic & Fourier analysis | 5 | 305,300 |
| functional analysis | 1 | 50,000 |
| geometry | 2 | 140,600 |
| topology & manifolds | 3 | 145,500 |
| probability theory & stochastic processes | 2 | 95,000 |
| statistics | 8 | 489,400 |
| numerical analysis & approximation theory | 1 | 60,000 |
| particle & continuum mechanics | 1 | 28,000 |
| mathematical programming | 1 | 54,000 |
| total | 51 | 2,759,500 |

The Large Grants are almost exclusively dedicated to academic institutions. These Large Grants have been awarded after a rigorous assessment process often involving international referees; in 1993, only 19% of initial applications were successful. The research supported is at

[20]Note that the ARC changed their classification scheme between 1993 and 1994. This explains why Tables 2.2a and 2.2b are presented separately.

the level of best international practice. Note that those Large Grants classified directly as the mathematical sciences (specifically as mathematical or statistical sub-topics in the Physical Sciences group; classification 1 above) amounted to $2.8 million in 1993 and $3.8 million in 1994, whilst the other grants (classifications 2 and 3 above) amounted to $5.1 million and $5.6 million during those years. This supports Table 1.2 in showing the spillover of basic research in the mathematical sciences to other disciplines.

Table 2.2b: 1994 ARC Large Grants classified directly under the mathematical sciences (classification 1 in the text).

| sub-topic | # of grants | $ |
|---|---|---|
| mathematical sciences | 5 | 191,200 |
| mathematical logic, set theory, number theory, group theory | 10 | 615,000 |
| algebraic structures | 3 | 122,700 |
| approx theory, Fourier/harmonic analysis, potential theory | 2 | 140,200 |
| functional and operator theory | 3 | 180,300 |
| geometry, topology | 4 | 212,800 |
| applied mathematics | 1 | 45,400 |
| numerical analysis, theory of computation | 3 | 198,700 |
| differential and integral eqns | 6 | 363,600 |
| optimisation, control theory | 6 | 331,500 |
| classical mech, fluids, optics, electromagnetism | 6 | 339,800 |
| applied math (other) | 2 | 105,800 |
| probability theory | 4 | 335,200 |
| stochastic modelling/analysis | 3 | 156,400 |
| statistical theory | 2 | 80,000 |
| applied statistics | 4 | 154,100 |
| math sciences (other) | 1 | 61,500 |
| incorrectly classified | 3 | 132,800 |
| total | 68 | 3,767,000 |

Box 2.3 contains a list of areas of strength in basic research in the mathematical sciences in Australia. The list is arguable of course; it is based on ARC Large Grants for 1993 and 1994. In forming this list, we used as a supplementary selection criterion that there had to be at least one group of sufficient size to carry out world class research in the topic.[21]

[21] Note the interesting point that *research effort in the mathematical sciences now requires a group* usually comprising research leader(s), academic collaborators, postdoctoral fellows, postgraduate students and research assistants. Usually at least half a dozen researchers are required. This represents a major change from the way research took place in Australia.

Table 2.2c: 1993 and 1994 ARC Large Grants awarded under classifications 2 and 3 in the text.

| group | # of grants (1993) | $ (1993) | # of grants (1994) | $ (1994) |
|---|---|---|---|---|
| biological sciences | 7 | 293,400 | 6 | 306,100 |
| chemical sciences | 2 | 76,000 | 3 | 127,400 |
| earth sciences | 3 | 171,100 | 7 | 371,100 |
| electrical and computer eng'g | 28 | 1,364,500 | 29 | 1,527,100 |
| civil, mech & chem eng'g, applied science | 45 | 2,026,000 | 35 | 1,741,400 |
| math and physical sciences (other than math sci) | 17 | 723,600 | 19 | 910,200 |
| social sciences | 13 | 460,300 | 16 | 577,800 |
| total | 115 | 5,114,900 | 115 | 5,561,100 |

**Box 2.3 Basic research in the mathematical sciences in Australia: strengths**

Taken at face value, Tables 2.2a and 2.2b provide a means to identify areas of research strength in the mathematical sciences in Australia. Arbitrarily, we might say an area is a strength if it is awarded more than 5 ARC Large Grants in any one year. Note that there is the possibility of incorrectly classified grants and considerable variability in the reporting level under the ARC's current Field of Research classification (used for the 1994 data). Note also that the members of the IAS at the ANU are not able to apply for ARC Grants; thus their contribution is ignored by the tables.

The ARC data gives as areas of strength: mathematical logic and set theory, number theory, group theory, differential and integral equations, optimisation and control theory, statistics, and classical mechanics/fluids/optics/electromagnetism.

Note the diffuseness of these groups. In specific areas such as optimisation and control theory, the Large Grants will generally be distributed across several departments.

Our criterion is simplistic. Strength is not especially a function of size nor need it be a function of financial support from the ARC; it is a function of excellence. To be 'excellent', the work should play a leading role in the development of mathematical science, naturally worldwide. Viewed from that standpoint we believe we could point to some half dozen areas of mathematical science in Australia that are plainly of the first rank; several other areas are possibles. There is some but by no means complete correlation with the dollar figures we report. The bottom line is, however, that Australia plays its proper role in international mathematical science.

We also accept the obligation to identify areas of weakness in basic research in the mathematical sciences. On the basis of observation by the Working Party during its site visits, the area of weakness in

Australia most appropriate to emphasise is the basic research framework underpinning operations research. This research field includes various aspects of optimisation, both deterministic and stochastic, modern topics such as neural networks, and many application areas such as rostering, scheduling and facilities location. The topic is of clear practical importance to the nation. The number of postgraduates in this field is considered to be insufficient to meet the industrial demand in Australia. This leads to:

**Recommendation 2**

- ☐ The Australian Research Council is encouraged to designate the field of Operations Research as a priority area for ARC grants, particularly as a Key Centre of Teaching and Research.

[**ARC**]

The Working Party also formed the view that the nation's mathematical scientists have much to gain by engaging more fully with SE Asia and the Pacific Rim. In part, this would help the export of education services to the region (see Chapter 3), but it is also a realistic reflection of the overall increased importance of this region over the time horizon of this review.

**Recommendation 3**

- ☐ To promote Australia's capabilities, mathematical sciences researchers are encouraged to give higher priority than is now customary to participation in scientific conferences in SE Asia and the Pacific Rim.

[**Mathematical sciences researchers, Professional Societies**]

To conclude this section, we find that current basic research in the mathematical sciences in Australia is varied, vibrant and involved in many of the most modern developments. There is widespread activity in universities, and the significance of the mathematical sciences has been acknowledged in the planning of government institutions such as CSIRO and DSTO. Financial support of the mathematical sciences by the Australian Research Council has increased substantially over recent years (see Section 2.4), some individual researchers are recognised as world leaders, and Australian groups have had significant impact in a variety of areas. Australian publications in the mathematical sciences remain at respectable international levels, particularly when the citation impact of these papers is considered.

Finding 1 encapsulates our views:

**Finding 1**

**It is essential for Australia to have a sound research base in the mathematical sciences for the following reasons:**

- **to be able to respond to new research ideas and opportunities**
- **to capture benefit through collaborative research and downstream technology transfer**
- **to educate future mathematical sciences graduates**
- **to contribute to the economic and cultural strength of the nation**
- **to benefit from international developments**

**In general, Australia possesses a sound research base, although certain sub-disciplines, among them operations research and financial mathematics, need to be strengthened.**

## 2.4 The Role of the Australian Research Council

Up to 1980, any university funding of mathematical research was a side effect of base funding with no significant grants coming from central schemes such as the Australian Research Grants Scheme (ARGS). There was some funding of postdoctoral positions through the Queen Elizabeth II Fellowships Progam administered by the ARGS, and the Rothmans company also funded some postdoctoral positions in mathematics through a competitive scheme. In the 1980s, the ARGS began to fund mathematical projects and provide postdoctoral support through their grants. This source of funding has grown in importance over the 1980–1995 period. The Fraser Government initiated a competitive scheme of Special Research Centres and in 1982 provided funding for the Centre of Mathematical Analysis in the Faculties of the ANU under the leadership of Professor N S Trudinger. This funding continued until 1991.

In 1988, the Australian Research Council (ARC) was formed and incorporated both the ARGS program and the Special Research Centres program. The ARC also introduced a Research Fellowship Scheme which incorporated the QEII scheme and had three grades of appointments: Postdoctoral Fellow, Research Fellow, Senior Research Fellow.

The (1992) Mission Statement of the ARC is: *to provide advice on research funding (and research policy) and to promote the conduct of research and research training of the highest quality for the benefit of the Australian community.* The five major benefits flowing to the community from research supported by ARC programs are stated to be

- contribution to the quality of our culture
- graduates of high quality
- direct application of research results
- increased institutional capacity for consulting, contract research and other service activities
- international links

The Department of Employment, Education and Training (DEET) provides funding for the following range of research support programs. These programs are administered by the Higher Education division of DEET, but generally awarded on recommendations of ARC. The recommendations are on the basis of competitive selection and international peer review. The programs are:

- The Research Grants scheme (Large Grants)
- The Small Grants scheme
- The Research Infrastructure program
- The Research Fellowships scheme comprising Australian Postdoctoral Research Fellowships, Australian Research Fellowships, Queen Elizabeth II Fellowships, Senior Research Fellowships, and International Reciprocal Fellowships
- Australian Postgraduate Awards
- Special Research Centres and Key Centres of Teaching and Research
- Industry/Higher Education Research Programs, including the Collaborative Research Grants Program and Australian Postgraduate Awards (Industry)
- Evaluation
- Grants to the learned academies

For 1994, the research funding budget was $303.6m compared to $280.9m in 1993. Large budget items were $107.2m for Research Grants (including Large and Small Grants, International Fellowships), $21.4m for Research Fellowships, $19.9m for Special Research Centres and Key Centres, $69.0m for Australian Postgraduate Awards, and $60.2m for research infrastructure. It needs to be noted, however, that the ARC budget when it was formed in 1988 included a 'clawback' of $65m from the pre-1987 universities' operating grants.

Prior to the mid 1980s, mathematical scientists were not particularly effective in winning grants from the ARGS. Up until 1984, no person whose primary interest was in mathematics and its applications had ever been a member of the ARGS Committee. Moreover, less than 2% of ARGS applications came from mathematicians. Detailed analysis and commentary on this situation has been provided by Anderssen[22] and Keats[23]. Keats concluded that

- The success rate of applications from mathematicians is no worse than the overall success rate for all academics.
- The number of grants per full time staff is, for mathematicians, about one half that for all academics.

He added that "The above two conclusions suggest very strongly that mathematicians as a whole are much less likely to apply for grants from ARGS than academics from some other disciplines. Unless this situation changes dramatically, mathematicians cannot expect to be influential on the ARGS committee. The above conclusions confirm the views expressed by Anderssen."[24]

A decade later, and the situation has changed significantly. As an overall indicator, Table 2.2a shows that ARC Large Grants for basic research involving the mathematical sciences amounted to $2.8 million in 1993, or approximately 3.7% of the overall ARC Large Grants. More precise information is given by the Robinson report on ARC funding for the mathematical sciences[25].

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[22]R S Anderssen, "Some facts about the ARGS", *Austral. Math. Soc. Gazette* **12** (1985), 31–34.

[23]R G Keats, "More on ARGS", *Austral. Math. Soc. Gazette* **13** (1986), 85–91.

[24]op. cit., p. 87.

[25]D W Robinson (Chairman), "Reviews of grants outcomes no. 9: mathematical sciences 1987-1991", *Australian Research Council Evaluation Program* (1993). It should be noted that this report considered only grants awarded directly under the mathematical sciences section of the ARC.

The Robinson report noted the following positive features:

- The ARC Large Grants Scheme has worked very beneficially for the mathematical sciences community in Australia during the period of review, 1987–1991. In particular, Large Grants for mathematical sciences research were 1.7% of total Grants in 1987 and had risen to 2.8% by 1991.
- The Large Grant funding of individual research groups has had very positive effects on the overall morale and ambience of various university departments.
- The Large Grants scheme has worked well in the mathematical sciences largely because the funding has gone to support concentrations of good researchers in internationally important areas.
- There was striking evidence that those who received significant funding during the review period produced much world class research.
- The principal uses of Large Grant monies in mathematics have been to support research assistants, postdoctoral fellows and programmers, to acquire computing equipment, and to support visitor programs.
- Peer review is commonly accepted as the most appropriate and acceptable method for supporting decision-making in a competitive grant environment.

The Robinson report also noted the following areas for concern:

- Much of the increase of funding of the ARC grants scheme was at the cost of the reduction of university base grants.
- The ARC support provided was often much less than requested.
- Project funding along the ARC lines tends to preclude a balanced strategy of funding of the sub disciplines and areas in accordance with their relative importance as perceived internationally.
- A significant number of research projects contain elements corresponding to topics within the remit of more than one ARC Discipline Panel or even of another Research Council.
- Various aspects of the peer review system created considerable unhappiness among the scheme's clientele.

The Working Party received many submissions relating to the ARC. The areas of concern listed above were still generally present, but also need to be supplemented by

- The very low success rate for initial applications (about 20%) is profoundly discouraging to researchers.
- If anything, the mathematical sciences have become more interdisciplinary and collaborative in nature, and researchers in these fields tend to feel they are denied adequate opportunities to bid for funds.
- Researchers in provincial universities, in small groups, and those at an early stage in their research career felt they were placed at a disadvantage when compared with applicants from large, mature research groups in big metropolitan universities.

After considering these submissions and data provided by the ARC, the Working Party came to the conclusions that

- The mathematical sciences were winning a reasonable share of ARC grants, to the significant benefit of the mathematical sciences community.
- There was no significant benefit to be obtained by switching to a two-stage application procedure, in which the first stage was a short expression of interest.
- Interdisciplinary research and mathematical sciences research that spills over to other fields is being effectively funded.
- Applicants from large mature groups in big metropolitan universities do relatively well in ARC applications. We feel that applicants from other institutions would do well to consider other funding sources, and we discuss this point in Chapter 7.

# 3

# Advanced Mathematical Services

In initiating this Review, the Australian Research Council sought to investigate the health of mathematical sciences research in Australia. As a result of wide discussions, the National Committee for Mathematics as co–ordinating body established a second main focus for the review, namely the provision of advanced mathematical services to users. In this chapter, we define and characterise these services, show how they are used to meet various socio-economic objectives, discuss their benefits to Australia, and anticipate what form these advanced mathematical services will take in the future. We also comment on technology transfer mechanisms for the mathematical sciences in Australia.

## 3.1 Definitions; The Need for a Research Base

We have already commented several times on the spillover of the mathematical sciences into research in other disciplines. But the applicability of the mathematical sciences is broader than inter-disciplinary or collaborative research – there is an instrumental role that is played by the mathematical sciences in many other fields of endeavour. In a landmark US-sourced review[26], Glimm found that

> The mathematical sciences are vital to economic competitiveness. They are a critical, generic, enabling technology.

To investigate this economic and service role of the mathematical sciences, we use the term 'Advanced Mathematical Services' to denote work based on mathematical principles and carried out by people with at least graduate level experience in the mathematical sciences. Practical examples of advanced mathematical services drawn from an Australian context include

[26] J G Glimm (ed.), *Mathematical sciences, technology and economic competitiveness*, Board on Mathematical Sciences, National Research Council (National Academy Press, Washington, DC, 1991).

- use of optimisation methods to develop more efficient crew rosters or timetables
- analysis of large and complex datasets – for example, from satellite data or from other forms of remote sensing
- design and analysis of clinical trials
- use of mathematical or computational models to improve the design of industrial equipment or processes
- financial applications of mathematics such as optimisation of investment portfolios or pricing of options
- economic forecasting
- simulation of manufacturing of mining or mineral processing operations
- use of mathematical techniques for layout of facilities such as warehouses, emergency centres or factories
- statistics applied to public health and epidemiology

An important aspect of the mathematical sciences is that they are *generic*, meaning that similar concepts and technologies are relevant to a range of applications. An excellent example is the numerical technology for solving sparse matrix equations, as required for many applications (see Box 3.1). Only one specialisation is required, not many. These concepts are illustrated in Figure 3.1.

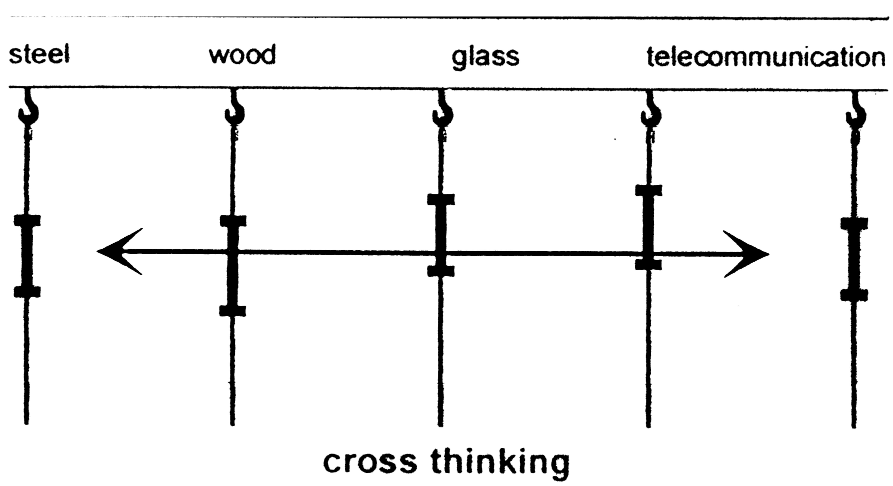


Figure 3.1: Particular techniques or mathematical sciences technologies, based on mathematical sciences research, can be applied in many different industry sectors. 'Cross thinking' based on generic technologies is efficient and leads to innovation.

In terms of the Australian Standard Research Classification (see the footnote to Recommendation 1), we now concentrate on applied research and experimental development, rather than basic research as emphasised in the previous chapter. Thus here we emphasise the utilitarian aspects of the mathematical sciences in which mathematics, statistics and computation are regarded as technologies that are applied to obtain solutions to practical problems.

Advanced mathematical services require a strong fundamental research basis for at least two reasons:

1. *Expertise*. It is notoriously easy to get wrong answers if mathematical technologies are applied outside their range of validity[27]. The best remedy for this problem is expertise brought to bear by practitioners with a thorough grasp of the technologies as acquired through basic research. Those who invent the methods, or develop extensions, are the ones who best understand them.

2. *Education and training.* We need to provide advanced mathematical services on a sustainable basis. For this, education and training of future practitioners is essential, and experienced campaigners with a track record in basic research have an essential role to play in this process.

**Box 3.1 Sparse matrices**

Many different applications require the solution of enormous sets of sparse equations, that is with many unknown variables, but only a few of them entering into any particular equation. To name just a few applications, large sparse systems occur in analysis of vibrations in structures, electric networks, in factorisation important to cryptomathematics, and in optimisation and computational fluid dynamics. Typically, a substantial fraction of the time required for large scale computations is dedicated to the solution of large sparse systems, so improvements in algorithms have a substantial benefit across a broad range of applications.

Systems of equations can be solved either directly or by iterative methods. For large sparse systems, direct solvers are not appropriate, so the only recourse is to use a specially designed iterative solver.

A widely used technique is the family of algorithms known as the Krylov subspace method, suggested in Russia some decades ago, but now widely adapted and implemented around the world. There are many associated research topics, including partial factorisation, pre-conditioning, efficient schemes for multiplication of sparse matrices and vectors, and the development of schemes for asymmetric systems. Vigorous research is under way to improve these sparse matrix solvers.

[27] P J Davis and R Hersch, *Déscartes' Dream: the World According to Mathematics* (Harvester Press, Brighton, Sussex 1986), pp. 159 *et seq.*: "Why should I believe a computer?"

## 3.2 The Nature of Advanced Mathematical Services

Our intellectual, political, cultural and economic lives are profoundly affected by ongoing needs for improvement in efficiency and effectiveness. In general, improvements are greatly facilitated by the use of models to understand physical and abstract processes. As soon as the demands of models progress beyond qualitative understanding to quantitative predictions, the mathematical sciences must be brought into action. This leads to our concept of advanced mathematical services as defined in Section 3.1.

The concept of 'modelling' merits some consideration. Models come in different forms – they can be physical models, often in miniature or of component parts, for example, of bridges or aeroplanes. They can be conceptual in nature, for example in biology, where the main causes and effects of complex systems are described. They can be used for direct experimentation and measurement, for example ship hulls in tanks or aeroplane wings in wind tunnels.

Here, we mainly consider mathematical and statistical models in which the key elements of physical and abstract systems are identified and then expressed in mathematical concepts. A very well known example is Newton's inverse square law for the gravitational force between any two particles of matter. With this simple mathematical model for gravitational force, together with Newton's laws of motion, it is possible to describe a vast range of astronomical and earthly observations. Other well known models based centrally on mathematical concepts are economic and weather forecasting models.

Many well known mathematical models are not perceived as such by the public. Australians have now heard of computer simulation as a real alternative to nuclear weapon tests. How many know that a computer simulation is the computer implementation of a mathematical model? How many know that the automatic control device that lands their jumbo jet safely is based on a mathematical model?

Once a mathematical model has been formulated, it needs to be solved for the application at hand. A huge range of mathematical technology then becomes available — systems of equations, linear algebra, calculus, measures for analysis of variability, and so on. Skilful practitioners will make sure that the model is validated against observations, and then the model is ready for prediction, interpretation and subsequent refinement. Over the last 30 years, ever more modelling activity is carried out on computers, to such an extent that computation is now routinely considered as a third strand of science along with theory and experiment.

Early major applications of mathematical sciences models were to high technology and defence science, for example to astronomy, ballistics, rocketry, electronics, aerospace and computing. The applications spill over to medium technology — automobiles, power generation, chemicals ... — and are also found in low technology (glass, minerals) and primary industries (crops, animals). The concepts of efficiency and effectiveness came later to low technology industries than to high technology industries, and many recent successes of the mathematical sciences have been in unlikely topics. Meanwhile, services have become a dominant part of all advanced economies, and the mathematical sciences have found wide applicability in topics like operations research, statistical modelling for the health industry, and finance.

## 3.3 Classification by Socio-Economic Objective

We now consider where advanced mathematical services have an impact. This is appropriately done using the Socio-Economic Objective (SEO) classification as developed by the Australian Bureau of Statistics. The SEO classification structure consists of four levels: division, subdivision, group and class as shown in Table 3.1.

Table 3.1: The SEO classification structure.

| division | subdivisions | group and class |
|---|---|---|
| defence | defence | 1 group, 6 classes |
| economic development | plant production & primary products | 4 groups, 30 classes |
| | animal production & primary products | 2 groups, 16 classes |
| | mineral resources | 4 groups, 32 classes |
| | energy resources | 4 groups, 16 classes |
| | energy supply | 5 groups, 25 classes |
| | rural-based manufacturing | 4 groups, 23 classes |
| | manufacturing | 12 groups, 58 classes |
| | construction | 5 groups, 26 classes |
| | transport | 4 groups, 12 classes |
| | information & communications | 6 groups, 28 classes |
| | commercial services | 4 groups, 13 classes |
| | economic framework | 6 groups, 27 classes |
| society | health | 3 groups, 45 classes |
| | education and training | 6 groups, 12 classes |
| | social development & community services | 6 groups, 24 classes |
| environment | environmental knowledge | 6 groups, 32 classes |
| | environmental aspects of economic development | 11 groups, 85 classes |
| | environmental policy & management frameworks | 3 groups, 3 classes |
| advancement of knowledge | natural sciences, technologies & engineering | 10 groups, 10 classes |
| | social science & humanities | 2 groups, 2 classes |

**Box 3.2 Mathematical sciences activity in radar research**
(based on a submission to the review by DSTO)

| application | topic | typical requirements |
|---|---|---|
| radar processing | signal processing<br>data fusion<br>tracking | Fourier techniques<br>wavelets<br>fuzzy logic<br>Kalman filters<br>neural nets |
| radar equipment | antenna modelling<br>equipment modelling | integral equations<br>linear algebra<br>optimisation |
| ionospheric sampling | propagation modelling<br>image processing<br>inverse problems | integral equations<br>regularisation techniques |
| signal propagation | propagation modelling | ionospheric fluid dynamics<br>wave propagation<br>perturbation methods<br>numerical solution of ODEs |
| scatter from target & ground | scattering theory | electromagnetic scattering<br>integral equations<br>spectral methods |

The mathematical sciences find application right across the spectrum of Socio-Economic Objectives. As examples, Boxes 1.1 and 3.2 describe respectively applications in cryptography and high frequency radar. Below we use five further examples to demonstrate the broad range of applications. Within any particular subdivision of the SEO codes, the mathematical sciences often find application in a vertically integrated way. Mining and mineral processing is an example with a pronounced Australian flavour. We show in Box 3.3 how the mathematical sciences play a key role at all stages in the sector. Box 3.4 describes benefits of applications of the mathematical sciences in the energy supply subdivision. As a last example, the role of the mathematical sciences in manufacturing is discussed in Section 3.5.

The preceding discussion gives an appreciation of the pervasiveness of the mathematical sciences in our everyday life. The economic importance of the mathematical sciences is captured in Finding 2 of this review:

**Finding 2**

**The mathematical sciences are critical to Australia's economic competitiveness and quality of life, and will become more so. The mathematical sciences are generic and enabling technologies. They are essential to the prosperity of many value-adding industries in Australia.**

**Box 3.3 Advanced mathematical services in mining and mineral processing**

| stage | typical mathematical sciences requirements |
|---|---|
| exploration | analysis of remotely sensed data |
| ore reserve estimation | geostatistics |
| mine planning | optimisation for scheduling |
| excavation | optimisation for scheduling<br>design of excavation equipment<br>blasting services |
| transportation & stockpiling | statistical sampling, optimisation |
| metal production | simulation, design of processes<br>computational fluid dynamics<br>statistical process control |
| fabrication | design of processes, control<br>simulation for plant layout |

To be sure, however, the key role played by the mathematical sciences is often not appreciated. This observation is so central that we describe it as Finding 3 of this review:

**Finding 3**

**The mathematical sciences make a vital contribution to many fields of research and endeavour. The importance of this contribution needs further emphasis because**

- **much work in the mathematical sciences is multi-disciplinary in nature**
- **there is a spillover of concepts and techniques from the mathematical sciences into other disciplines, particularly through methods and software widely used in those disciplines**
- **researchers in many other disciplines (including the social sciences) who would not describe themselves as mathematical scientists nonetheless make extensive use of mathematical and statistical concepts**

## Mathematical science at work

*Example 3.1: Biometrics*

This field is one in which Australia has a distinguished international reputation because of the importance of primary industry to the Australian economy and the leading role played by CSIRO and other government biometricians over three decades. As an example, current biometrical work under way in CSIRO Institute of Animal Production and Processing includes: design of sampling schemes and experiments, regression analysis, training in the use of statistics packages for PCs, multivariate analysis, distribution free analysis, and quality control. Recent topics in which the biometrical work has had valuable input include: design and analysis for commercial taste tests, predictive microbiology, statistical analysis for a project investigating Japanese taste preferences, and prediction of grain quality. Similar important biometrical work is under way in plant research, environmental research, fisheries and other fields.

*Example 3.2: Queensland Department of Primary Industries*

The Queensland Department of Primary Industries has visionary views on the importance of advanced mathematical services. Areas of current need identified by DPI include: numerical computation on supercomputers and massively parallel systems (*e.g.* on vegetation as affected by drought), algorithms for data compression, the integration of large scale models (weather, ocean circulation, hydrology, ...) to predict stock carrying capabilities, and decision support models for a range of applications.

In a submission from DPI, a senior staff member said “Our work required numerical skills. Through a university contact we approached the University of Queensland ... we set up a joint project that has worked very well. We are completely satisfied by the project work, but I feel frustrated in that mathematics has so much more to offer that we have difficulty bridging the gap. ... Algorithms and their application are at the heart of what we are trying to do. I am afraid there is not sufficient understanding from both mathematical and user perspectives. ... DPI has a cost benefit ratio of 9:1 for every dollar put into the university system. I can’t speak too highly of the benefits.”[28]

[28]submission to the review by Dr Dick Schoorl, Special Projects Officer, Qld DPI.

*Example 3.3: Medical statistics*

The use of statistical methodology in medicine is widespread. Such use is not surprising because diseases and their treatment abound with variability, and there is a consequent need for special skills like statistical data analysis, design of experimental trials, and epidemiological studies on the spread of diseases. The spread of AIDS is a topical example in which forecasts for future cases have major economic, cultural and human implications. We take it for granted that the forecasts are accurate, but it is valuable to remember that they are based on mathematical and statistical models which are usually implemented on computers. The work of mathematical scientists is to develop and confirm those underlying models.

Several Australian universities are active in statistical research with application to medicine and health. For example at La Trobe University the School of Statistics has research activities in alcohol related road deaths, vaccination schedules for childhood immunisation, predicting the occurrence of AIDS, analysis of family data with applications to genetic disorders, single case studies for stroke victims, case-mix funding for hospitals, and analysis of cell lineage data. The social, medical and human importance of this work is clear.

*Example 3.4: The financial sector*

In recent years, the financial sector of the economy has become a major employer of mathematical sciences graduates and postgraduates. Most major banks, investment houses, and stockbrokers employ quantitative analysts. In addition to private sector employment, there is also large scale employment of quantitative analysts in state and federal government agencies. We estimate that there may be as many as 50 such large enterprises in Australia with up to 10 such analysts each.

The review received a number of submissions from analysts in the finance sector. One pointed out that intake is at three levels: 'heavyweights' (or research specialists) in topics like stochastic calculus and numerical methods, PhDs as members of dealing teams, and graduates as members of research teams or trainee dealers. Potentially employable students need intelligence, to have good undergraduate degrees in the mathematical sciences, to have good computing skills, and to be sensible mature people. At the high end, the work carried out by the quantitative analysts uses very sophisticated mathematical concepts; for example, one Chief Analyst cited the following topics in his submission: real analysis and probability, continuous martingales, stochastic calculus, stochastic equations in infinite dimensions, time series, integer programming, . . . [transcript of submission]

Another senior manager cited the following mathematical needs: optimisation techniques (integer and non-convex optimisation), stochastic processes, martingales and associated statistical techniques, non-linear dynamics and chaotic modelling, and stochastic control theory. All need to be understood in the context of how they can be numerically implemented, and an ability and willingness to write appropriate computer code is almost mandatory. This senior manager pointed out as barriers to success: the radically different cultures between academia (where the graduates and specialists come from) and the industry itself, and the overall lack of human resources partly as a function of Australia's size. [transcript of submission, slightly modified]

*Example 3.5: Actuarial science*

Actuarial science — the financial management of risks in institutions, with an emphasis on insurance — is a subset of the financial sector. It is pertinent to note that the standards of the actuarial profession are tightly controlled by accreditation by the Australian Institute of Actuaries. There are two actuarial studies departments in the country (Macquarie University and the University of Melbourne) in which research and rigorous teaching take place. Nowadays most recruits into the profession have a commerce degree, with a minority of these having mathematics as their degree major; thirty years ago, 90% of actuaries would have been mathematics graduates. This is because actuarial studies were established, first at Macquarie and then at Melbourne, in faculties such as Economics and Commerce. Also, information technology developments have meant that there is now less emphasis on mathematical wizardry in the actuarial profession and more emphasis on interpretative skills within a commercial environment. The professional examinations for actuaries do not cover a range of important topics in the mathematical sciences which are widely used elsewhere in the finance sector: simulation techniques, stochastic processes, advanced statistics (such as Kalman filtering), and statistics from other disciplines (such as survival analysis for specialised life insurance products).

The Working Party gained the impression that the actuarial profession is not characterised by research innovation. The actuarial profession has been slow in incorporating new mathematical sciences developments into their required professional subjects. On the other hand, the profession does use other groups to teach specialised subjects — for example, they use the Securities Institute of Australia to lecture on financial topics. In general, the Working Party feels that the actuarial profession would be better served if they were more closely engaged with the mathematical sciences community, particularly through service teaching.

## 3.4 Provision of Advanced Mathematical Services

We now examine how advanced mathematical services are provided in Australia. The following principal mechanisms were evident in submissions to the review:

- *Consulting by academics.* Many mathematical sciences departments indicated that staff members undertake small scale industrial consulting work. In some cases, this takes place on an individual basis, whilst in others it is organised either through the department or through consulting groups formed in the department. Intra–university consulting is quite common, particularly for statistical groups, although problems in its execution were frequently noted, particularly how this work should be costed and paid for. Intra–university statistical consulting provides valuable training for graduate students and contributes to the research of the department, quite apart from benefits to the clients. Statistical intra–university consulting takes place at substantial levels at several universities including Melbourne and ANU.

- *Private companies.* In the course of the review, the Working Party made contact with some five specialist companies critically dependent on the mathematical sciences for their operations. The main fields of work are statistical consulting and decision support (or more generally operations research). Some of these companies evolved from consulting activity in university departments, others from government departments, and one from a management consulting firm. The biggest of the companies had approximately 40 staff members, the smallest about five staff. In most cases, the key mathematical sciences capabilities of the firms have to be wrapped in information technology products, supplemented by marketing and management skills.

- *Collaborative research.* Examples of collaborative research have been given already in this chapter, but there are many other activities that were described in submissions to the review. In particular, the Cooperative Research Centres Program employs many people with advanced mathematical skills. An example from the CRC for Aerospace Structures is given in Chapter 1. These collaborative research activities are largely carried out by academics or government staff seconded to CRCs.

  It is noteworthy that a few other government programs sponsor collaborative research for which mathematical scientists can bid. These include ARC Collaborative Research Grants and generic grants of the Industrial Research and Development (R&D) Board. We return to this point in Section 3.6.

- *Employment of mathematical scientists in big companies.* A number of Australian enterprises are large enough that they have R&D laboratories with their own mathematicians and statisticians. BHP, CRA, Telstra and many banks lie in this category.

- *Government research organisations.* A large number of government departments employ mathematicians and statisticians to provide advanced mathematical services. Large groupings occur in CSIRO (with approximately 100 staff in its Division of Mathematics and Statistics, and probably as many mathematical scientists again in other Divisions), DSTO (with probably more than 100 mathematical scientists educated to masters or postdoctoral level), the Australian Bureau of Statistics (with more than 60 staff at least at honours level carrying out statistical work), and the Australian Bureau of Agricultural and Resource Economics (with a dozen specialists, mainly with statistical training).

  It is worth noting that some of these government departments have a specific obligation to obtain a significant fraction of their budgets from industrial and other users of their research. This is particularly true for CSIRO Division of Mathematics and Statistics which now receives more than 40% of its budget from non-appropriation funds. See Section 3.6 for more discussion of this Division.

Our evidence suggests that the total number of people providing advanced mathematical services to the Australian economy is substantially larger than the number of academic mathematical scientists. This large body of people carries out work which is vital to the nation, but the pivotal and critical role of the mathematical skills they use is largely unappreciated because of their diverse range of activities and mode of employment. This *diffuse nature* of advanced mathematical services is quite different from the application of disciplines like chemistry in the Australian economy, in which there are a handful of large firms operating in a clearly defined economic sector. One thing that can be stated with certainty is the Glimm finding: "The mathematical sciences are vital to economic competitiveness. They are a critical, generic, enabling technology."

The key traits and competencies required of providers of advanced mathematical services are a little different from those for academic researchers, a point which can cause some tension. Academic researchers in the mathematical sciences are characterised by research innovation, problem solving skills, and the ability to apply their knowledge to new fields of endeavour. They need in-depth knowledge of their particular research field, written communication skills so they can publish their work in learned journals and apply for grants, and often (but by no means always) teaching skills. The most successful researchers usually have high need for achievement but, at least in the stereotype, low needs for power and affiliation. The spirit of enquiry provides the motivation for much academic research; the importance of that research to the nation is usually justified by the confident assertion that Australia needs a sound research base and by an allusion to the cultural merit of the research work.

Providers of advanced mathematical services need more than just these traits and competencies. Plainly they need technical expertise and computing skills as do their academic colleagues. There is however a much more prevalent need for communication and interpersonal skills, for the ability to work in teams, and for customer focus and marketing. The rewards for providers of advanced mathematical services are not just kudos from their peers, they are more likely to include financial benefit and the power to direct a group of technical employees. The basic motivation for advanced mathematical service is not just abstract and aesthetic; it includes the desire to play a role in ensuring that some utilitarian goal is successfully attained.

The potential for a clash of attitudes certainly became evident when government laboratories were directed away from a basic science emphasis and towards a customer focus. University departments experience analogous difficulty in their attempts to obtain direct external funding for their research. Bridge-building is required; we examine this point in Section 3.6.

When academic groups do turn to providing advanced mathematical services directly to external users, some period of adjustment is required. It is necessary to learn how to charge for work done, and the extent to which the department should be compensated for the use of university facilities. There is also an obligation on mathematical scientists embarking on consulting work to recognise that they have chosen to become ambassadors for their profession, and that it *is* important that the overall prestige of the profession be increased by their work. It remains a vexing question just how to reward academic staff who carry out consulting work. It is not appropriate to suggest that the nett payments for the consulting are reward enough; that does not take into account the hoped-for overall benefits to the profession though increased public awareness and prestige, the broader spread of funding sources, and the general contribution to a culture of innovation in Australia. When consulting work is carried out by academics, it is important that the full costs be charged in order to prevent unfair competition to private providers of advanced mathematical services. The views of the Working Party are summarised in Recommendation 4.

**Recommendation 4**

- ☐ Universities should enhance their mechanisms for recruiting and rewarding academic staff who, through consulting and similar activities, provide advanced mathematical services to external customers. Consulting should be fully costed, and it should be managed through departments and not on an individual basis.

[**AVCC, Deans**]

## 3.5 Benefits to Australia; Emerging Opportunities

It is a happy thought to imagine that the overall contribution of a profession to the nation can be precisely evaluated by a cost-benefit analysis. If, as most mathematical scientists would believe, their profession is outstandingly cost-effective, then there would be an iron-clad case for demanding additional resources. Sadly, this is fanciful.

Certainly, formal mechanisms exist for carrying out cost-benefit analyses. Indeed these mechanisms are based on simple mathematical principles aimed at working out the nett present value of a depreciating investment made over a number of years.[29] But the difficulty is in the assumptions and data to be captured in the mechanism. We have already commented on the critical role of the mathematical sciences in team efforts, for example in developing an information technology product for crew scheduling, or in a R&D program sponsored in another discipline. It is generally exceptionally difficult to put a value on the extent of the mathematical contribution, even if there were a willingness by the owner of the work to release confidential commercial information. Moreover, in cost-benefit surveys one might well claim the total value of the project on the premise that one's contribution was critical, even though it was only a few per cent of the total investment. This obviously leads to double counting.

Sometimes it is possible to get unambiguous assessments. Box 3.4 describing work carried out by CSIRO Division of Mathematics and Statistics for the Electricity Trust of South Australia is one such case. In other cases, the essential role of the mathematical sciences is affirmed by those who own the overall project, and the value of the mathematical sciences is demonstrated by the fact that those owners continue to fund further work on advanced mathematical services. An excellent example here is the cryptomathematics work cited in Box 1.1.

[29]The mathematical principles underlying cost-benefit analyses provide a nice metaphor for the vital but seldom-appreciated role of the mathematical sciences.

The following quote from a very senior industry R&D manager in Germany emphasises the principle:

> Die heute in der industriellen Forschung und Entwicklung geforderten Höchstleistungen können nur mit zunehmendem Einsatz mathematischer Methoden erfüllt werden. Ein Beispiel hierfür sind Simulationsmethoden, mit denen bei der Entwicklung komplexer Produkte der notwendige Versuchs- und Konstruktionsaufwand deutlich reduziert werden kann.[30]

**Box 3.4 Risk assessment for ETSA**

It is known that fires can result if uninsulated power lines clash in high winds leading to a shower of sparks. The most cost-effective way to prevent this cause of fires is to replace bare wires with covered wires. This reduces the fire-start potential to almost nil, and is much cheaper than placing the wires underground.

The Electricity Trust of South Australia has 10,800km of distribution lines in high bushfire risk areas and an estimated replacement cost for these lines of $400 million. Clearly ETSA needed a sound basis for deciding which lines should be upgraded.

This basis was provided by CSIRO Division of Mathematics and Statistics. High risk areas were identified and ear-marked for introduction of insulated wires. Risk factors included the state of maintenance of the powerline, the likelihood of a fire spreading if it started, and the likely amount of damage that a fire could do if it ran out of control. This risk strategy was then incorporated into a software model which enabled ETSA staff in the field to assess risks in short sections of wire using a portable computer.

This prudent and defensible asset management will result in savings of up to $250 million and will help ETSA establish these practices as an industry benchmark.

This review has the difficult task of forecasting developments for the mathematical sciences over a 10–15 year horizon. We can assume that events and innovations, as yet unknown, will play a major role. To conclude this section, we summarise some known trends in the Australian economy, briefly review two major US documents, and try to identify emerging opportunities for the mathematical sciences.

[30] Quote from a letter to Prof Neunzert by Prof Dr-Ing Hartmut Weule, Leader of the Research Department, Daimler Benz, stating that "The high performance demanded in today's industrial R&D can only be achieved by increased involvement of mathematical methods. An example is simulation methods, which can clearly reduce the investigation and development costs of complex products."

Some obvious trends that have developed in Australia in recent times include

- whole system analysis, or optimisation of a complete system rather than components of it
- outsourcing of non-key activities, including R&D (which includes the mathematical sciences)
- rapid prototyping through use of simulation
- quality management and continuous improvement
- increased specialisation facilitated by information technology developments
- the onset of the virtual corporation ... small, flexible, highly specialised enterprises, with blurred boundaries to suppliers and customers
- privatisation and a smaller role for government

Related material has been discussed at length by Friedman *et al.*[31] Their document examines the enabling role of the mathematical sciences in advanced materials, manufacturing processes, process control, statistical quality improvement, cost-based performance measures and benchmarking. Six emerging manufacturing technologies are highlighted and five emerging management practices are examined. The major conclusions of the report are

- A revolution is transforming the manufacturing process and the organisation of industrial enterprises.
- New technologies and management practices enabled by the quantitative, that is, mathematical and computational sciences are among the driving forces of this revolution.
- In their generic and precompetitive aspects, these technologies are a joint responsibility of academia, government and industry. [32]

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[31] Avner Friedman, James Glimm & John Lavery, *The mathematical and computational sciences in emerging manufacturing technologies and management practices* (Society for Industrial and Applied Mathematics, Philadelphia, 1992, 87pp.)

[32] ibid., p.3.

The recommendations of the document are too long to be reproduced here in full, but they call for

- rapid advances in the quantitative sciences to support the pre-competitive aspects of the infrastructure needed for world class manufacturing
- more effective use of mathematical and computational methods in management practices as part of a cooperation between industry and academia
- the ongoing reform of mathematics education, both at K-12 level and in universities, to support the needs of manufacturing

The executive summary for the document concludes: "research in the mathematical and computational sciences plays an important role in creating the new technologies and management practices of the world's leading manufacturing enterprises."

On a narrower but still important topic, Geoffrion[33] has reviewed the situation for quantitative sciences in management science and operations research (MS/OR). Geoffrion identifies four *forces* of historic importance (the microcomputer and communications revolutions, the dispersion of MS/OR in industry, and the universities' unbalanced reward structure), three major *trends* (rapidly disseminating MS/OR tools, declining enrolments of US nationals, and persisting management apathy towards MS/OR), and five outstanding *opportunities* (ride the computer and communications revolutions, support dispersed practitioners, focus on the service sector, stress embedded applications, and go into the quality business).

What then of emerging trends and opportunities for the mathematical sciences in Australia? The situation for management science and operations research, as identified by Friedman *et al.* and Geoffrion in the USA, remains broadly valid for Australian conditions. There is increasing emphasis on the analysis of large and complex data sets in industry and business. The use of the mathematical sciences to process and analyse data (often collected by remote sensing) in the form of images is increasing rapidly. There will be increasing mathematisation of other disciplines to model physical and abstract systems. The role of the computer will become ever more important. And there is always the unpredictable element, for example the practical importance in cryptography and data transmission of number–theoretical principles and techniques.

[33] Arthur M Geoffrion, "Forces, trends, and opportunities in MS/OR", *Operations Research* 40 (1992), 423–445.

## 3.6 Technology Transfer Mechanisms

In carrying out this review, the Working Party found that Australia has an excellent research base in the mathematical sciences. Moreover, the previous section describes the present and anticipated national benefits which flow from the use of advanced mathematical services. We cannot stress too highly the importance we ascribe to the contribution of advanced mathematical services towards developing a culture of innovation in Australia. Overall, however, there is a relatively immature and weak connection between suppliers and users. This is the topic we address here.

To be sure, there are highlights in this connection, and some successful bridge-building and technology transfer mechanisms exist. Of these, the highest profile one is the Mathematics-in-Industry Study Group which is described in Box 3.5. More generally, technology transfer – or the provision of advanced mathematical services – takes place in a variety of ways as described earlier (Sections 3.2-3.4).

**Box 3.5 The Mathematics-in-Industry Study Group**

From 1984 to 1993, CSIRO Division of Mathematics and Statistics held an annual problem-identification and problem-solving workshop known as the Mathematics-in-Industry Study Group (MISG). Since 1994, the MISG has been organised by the Department of Mathematics at the University of Melbourne.

The MISG was based on a long-running initiative in Oxford. It is a weeklong meeting at which 8 or so industrial problems that need mathematical work are addressed by delegates. A framework is developed whereby problems can be tackled and, where possible, progress is made towards solving the problems. Companies pay a modest fee to have their topics considered. In recent times, more than 100 delegates have attended each meeting.

The MISG has had notable successes, particularly in helping to build an awareness in Australian industry of the power and capability of mathematical modelling. The concept helps to build better relationships between academics and industrial researchers; it also points clearly to the need for more operations research capability in the country. An international patent resulted from one of the early meetings, and follow-up consulting and collaborative work with industry continues to occur. Also, the meetings have helped to generate a significant amount of research, particularly at postgraduate level.

Government programs which can be used to facilitate technology transfer from mathematical sciences researchers to industrial users include:

- *Australian Research Council:* Three principal mechanisms exist.
  - Collaborative Research Grants. The total funding available in 1994 was $10.6 million. Of the 180 projects funded, only three were in the mathematical sciences.
  - Special Research Centres and Key Centres of Teaching and Research. The total funding in 1994 was $19.9 million. None of the 18 Special Research Centres are based on the mathematical sciences. Only one of the 34 Key Centres is related to mathematical science (in fact through education).
  - Australian Postgraduate Awards (Industry). 125 of these awards were made in 1994. Of these, none were listed under the mathematical sciences. In 1993 and 1994, only one and two awards respectively went to the mathematical sciences.
- *Cooperative Research Centres:* More than 60 CRCs now exist. Although the mathematical sciences play an important role in some of them, none are based primarily on the mathematical sciences. (See Chapter 8.)
- *Industry R&D Board:* The Board aims to increase the level and commercial success of industrial R&D undertaken in Australia, and makes competitive grants for this purpose. Two such grants in the mathematical sciences in recent times were for train scheduling and computational fluid dynamics. Overall, however, this program is not widely known or used by the mathematical sciences community.
- *CEED:* This program has both educational and industrial missions. It provides training assistance for senior undergraduates, but was only referred to by one university mathematical science department during our site visits.

Overall, there is very low participation by mathematical scientists in these programs. Consideration of the various sorts of Centres is so important that Chapter 8 is devoted to the issue. There would appear to be scope for academic mathematical scientists to be more vigorous in bidding for Collaborative Research Grants and Australian Postgraduate Awards (Industry).

We now discuss more carefully the role of the universities, government laboratories, professional associations, industry, and government programs.

*The universities*

One major activity of mathematical sciences departments is service teaching. This is not an *advanced* mathematical service. Nor would we so classify normal undergraduate teaching. Nevertheless, much departmental work has customers in mind: future employees, students to be educated, supporters to be cultivated, and external collaborators. University departments need formal mechanisms to obtain advice and feedback about their courses and prospective activities. Some departments already have such mechanisms in place.

**Recommendation 5**

- ☐ All mathematical sciences departments should have external advisory mechanisms to assist in the development of strategic objectives, to inform the department about research opportunities, and to get external feedback on the suitability of existing and proposed courses.

[**Heads of Department, Deans**]

A number of Australian universities have formal activities aimed at increasing the industrial relevance for their work. For example, the University of Queensland's Department of Mathematics has a 'Centre for Industrial and Applied Mathematics and Parallel Computing' to help focus its work with outside agencies. The University of South Australia has a 'Centre for Industrial and Applied Mathematics' in its Department of Mathematics to cater for its research (which is generally industrially directed) and consulting work. Despite these initiatives and similar ones in other universities, no such Australian activity could be classified at the level of international best practice.

Friedman & Lavery[34] offer valuable advice. They discuss important questions such as what is industrial mathematics, what skills are needed for it, and why there are not more mathematical scientists in industry. They point out that collaboration between an academic scientist and an industrial user requires crossing cultural barriers. It takes a significant investment of time for each of them to learn the culture of the other. Often, mathematical sciences issues are addressed in industry, sub-optimally, by in-house scientists and engineers with mathematics and statistics backgrounds.

Friedman & Lavery describe features of industrial mathematics programs in various US universities and they describe the important steps required to set up such a program, including the critical one of

[34] Avner Friedman & John Lavery, *How to start an industrial mathematics program in the university* (Society for Industrial and Applied Mathematics, Philadelphia, 1993, 37pp.)

establishing the relationship with industry. The programs they describe span undergraduate, postgraduate and postdoctoral levels.

The overall justification for and benefits of these programs are described thus by Friedman & Lavery:

> By introducing an industrial mathematics program, a mathematical sciences department will be providing to its students an immense opportunity for greater and deeper contributions in all areas of the natural and social sciences, engineering, and technology. By introducing such a program, the department not only creates an atmosphere of trust and confidence in society as a whole that the mathematics sciences community, while rightfully having many concerns of its own, is also ready to contribute to the solution of larger problems. Every part of the mathematical sciences community, including parts with no direct interest in industrial mathematics, will benefit from the presence of industrial mathematics programs side by side with many other mathematical sciences programs. Industrial mathematics programs should be given increasing acceptance and reward in our community.[35]

There is one other important initiative accessible to university departments — the provision of mathematical sciences education services to students from SE Asia. Sexton[36] describes the earnings of Australia in 1992–93 from the provision of overall university education services to foreign students: $95 million on education consultancy and correspondence courses delivered overseas, $696 million on education fees for foreign students in Australia, and a further $626 million in living expenses for these students. Mathematical science in Australia, in its research and university teaching aspects, is more advanced than in many countries in SE Asia, and there is an opportunity to improve collaboration and cultural understanding through the provision of educational services in the mathematical sciences; the opportunity to increase Australia's foreign earnings is a bonus.

*Government laboratories*

The provision of advanced mathematical services in many government laboratories is a relatively straightforward issue: these laboratories are large enough to recognise the need and to fund staff to carry out the work. In government laboratories, advanced mathematical services

[35] ibid., p.iv.

[36] Elizabeth Sexton, "Top marks for education exports", *The Bulletin* (January 17, 1995), 65–68.

mainly play an in-house role. The work at DSTO and ABS is an example. At the high end, the advanced mathematical services blend into collaborative research, a point made forcefully in one submission:

> We disagree with the primarily instrumental role of mathematics as a 'service' implicit in this review. It is an integral component in the task of developing a better physical understanding of the real world. [Dr John Finnigan, CSIRO Centre for Environmental Mechanics]

One particular government group has a wider professional role — CSIRO's Division of Mathematics and Statistics has the vision and mission statements:

*Vision: Australian enterprises thriving through effective use of mathematics and statistics.*

*Mission: The Division will develop mathematical and statistical products and services which will be employed for the benefit of Australia and/or Australian enterprises.*

In pursuit of this wider role, DMS sponsored the Mathematics-in-Industry Study Group (see Box 3.5) for many years, and now provides expertise to industrial users and other CSIRO divisions in mathematical and statistical modelling, computational fluid dynamics, operations research, quality improvement, image analysis, time series analysis and remote sensing. Box 3.4 gives one example of the impact of the Division's work. In accord with government policy, more than 40% of DMS's budget comes from non-appropriation funds[37]. Because of the generic nature of the mathematical sciences, there is clear benefit in retaining such a body of researchers under one umbrella rather than dispersing them amongst CSIRO divisions. There is also benefit in charging such a group with the responsibility to build bridges between professional mathematicians (largely in universities) and potential industrial users, thereby helping to develop awareness in industry of economic benefits that are accessible and also helping to develop a culture of innovation in Australia.

*Professional societies*

Professional societies can help develop a culture whereby the nation can gain direct benefit from its fundamental research strengths. Specialist interest groups with an industrial focus can be set up, activities can be initiated that will appeal to industrial members, and professional societies can be a powerful voice in shaping government opinion.

[37] CSIRO has an overall obligation to earn 30% of its budget from non-appropriation funds. Once corporate overheads are accounted for, operational units have much higher earning targets.

Of the societies listed in Chapter 1, ASOR is the one with the most industrially-directed activities, whilst AustMS is the one with the most to gain by strengthening its emphasis on industrial activities. At present, AustMS's division, ANZIAM, does play a modest role in supporting technology transfer and bridge building activities, for example by financial contributions to the MISG and occasional conference activities.

In general, however, Australian professional societies in the mathematical sciences do not have the financial resources to sponsor major activities which increase technology transfer between the universities and industry. In this regard, Australia is at a disadvantage with Europe and the USA where, for example, SIAM (Society for Industrial and Applied Mathematics) in the USA is large enough to sponsor major technology transfer activities and to fund important studies on the nature and benefits of this work. Several of SIAM's studies are extensively cited in this report.

*Government programs*

The uptake of advanced mathematical services by industry will have economic benefits to Australia. Because of the pervasive influence of the mathematical sciences, we feel that increased uptake of advanced mathematical services will help develop a culture of innovation in Australia.

But the mechanisms by which mathematical sciences technology is transferred to users in Australia are weak. There is a gap between potential suppliers and potential customers. This situation can be improved by more attention to communication, by support for existing successful activities, and by new initiatives that will require modest levels of additional funding. Some explicit suggestions are made in the Recommendation below. Of these, the CRC initiative is the largest and this topic is addressed in detail in Chapter 8. Responsibility for these improved mechanisms belongs with government and the profession.

**Recommendation 6a**

- ☐ Academic mathematical scientists are encouraged to bid more vigorously for ARC Collaborative Research Awards and Australian Postgraduate Awards (Industry).

**[Mathematical scientists]**

**Recommendation 6b**

- ☐ The Mathematics-in-Industry Study Group should be continued, preferably as part of the activities of a CRC for Industrial Applications of the Mathematical Sciences. Should such a CRC not be established, then the Australian Mathematical Society (through ANZIAM) is encouraged to co-ordinate ongoing arrangements for the Study Group.

[**Chief Scientist, ANZIAM**]

**Recommendation 6c**

- ☐ Mathematical scientists are encouraged to communicate more effectively with the media and general public.

[**Mathematical scientists**]

**Recommendation 6d**

- ☐ CSIRO is encouraged to continue its funding support for the activities of CSIRO Division of Mathematics and Statistics. This Division should continue to operate on a disciplinary basis.

[**CSIRO**]

**Recommendation 6e**

- ☐ DIST is encouraged to develop a specialist program so that small to medium enterprises (SMEs) have access to advanced mathematical services. The benefits of this program should be communicated. SMEs need to be assured of access to the 150% taxation benefit for advanced mathematical services provided to them.

[**DIST**]

**Recommendation 6f**

- ☐ Academics are encouraged to seek secondments to industry during periods of study leave. Where payments are made by industry for these secondments, taxation relief should be available to the employers.

[**Mathematical sciences researchers, ATO**]

# 4

# Human Resource Issues

## 4.1 Age Structure of Mathematical Sciences Departments

Australian universities went through a major period of expansion in the two decades prior to 1980. After this rapid expansion ceased, recruitment of staff at lecturer level took place at a very low rate, and the result is an age distribution which is heavily skewed to the 45 and upwards group. The age distribution is shown in Table 4.1.

Table 4.1: Age distribution of permanent academic staff in mathematical sciences departments in Australian universities (data obtained by questionnaire).

| age group | male | female | total |
|---:|---:|---:|---:|
| $< 25$ | 0 | 3 | 3 |
| 26–30 | 8 | 4 | 12 |
| 31–35 | 32 | 7 | 39 |
| 36–40 | 74 | 18 | 92 |
| 41–45 | 76 | 19 | 95 |
| 46–50 | 116 | 9 | 125 |
| 51–55 | 126 | 8 | 134 |
| 56–60 | 53 | 1 | 54 |
| $> 60$ | 16 | 3 | 19 |

There has been a long period of very low recruitment of new academic staff; for young PhD graduates, a sequence of temporary postdoctoral appointments is commonplace, and is not at all guaranteed to lead to an eventual continuing appointment. It is still common for outstanding students to take their doctorate overseas; these students have difficulty in regaining any sort of foothold in Australian universities.

The age distribution of permanent academic staff reminds us that researchers in the mathematical sciences are often said to do their best work by a relatively early age, say by 35–40. The evidence for such a belief is not very compelling, but in any case, universities do not have strong mechanisms for making the best use of those whose most productive years are past.

Data collected by the Working Party suggests that the number of PhD graduates in Australia is likely to jump sharply beyond the 30–35 *per annum* which has been the average rate for the past 20 years. Thus the pool of talent from which replacements will eventually be made is likely to increase significantly. (See Section 4.4 for a discussion of the number of mathematical sciences PhD graduates in Australia, past and forecast.)

In analysing the implications of Table 4.1, we need to bear in mind the likelihood that non-compulsory retirement will become the norm throughout Australia during the time horizon of this review. However, current superannuation arrangements and voluntary early retirement schemes probably guarantee a rush of retirements similar to that which could have been expected in the presence of compulsory age-related retirement. Indeed non-compulsory retirement may allow a smoother transition than might otherwise have been feasible. The principal present problem is how to retain current promising postdoctoral researchers in the system given that permanent jobs will not become available in any significant numbers for another decade. That retention seems essential if we are to have appropriately experienced replacement staff in adequate numbers.

Replacement of academic staff also depends on Australia's economic fortune compared to the rest of the world. At the moment, there is abundant opportunity for recruitment from the countries in the former Soviet Union, but this is a short term phenomenon. On the other hand, the value of the Australian dollar has fallen by 50% on a trade weighted basis during the past 20 years, and good candidates have the opportunity of much higher paid jobs overseas. The Working Party heard of difficulties in recruitment in commercially important and rapidly developing areas such as operations research and image analysis.

Flexible and creative solutions are required to capitalise on the expertise that we have in the nation's universities whilst ensuring continuity in the profession, particularly by provision of appointments for postdoctoral researchers. We therefore make the following recommendation:

**Recommendation 7**

- ☐ Universities must develop plans to address difficulties caused by the present age structure in mathematical sciences departments. Consideration should be given to attractive early retirement plans and mechanisms for retaining promising postdoctoral researchers and grooming future leaders in the profession.

**[AVCC, Deans, Heads of Department]**

## 4.2 Gender Structure of the Mathematical Sciences

Historically, many professions including the mathematical sciences have been male-dominated. However, gender imbalance is now much less pronounced in many professions than it used to be. Table 4.1 clearly displays the fact that there remains a pronounced gender imbalance in academic mathematical sciences departments. Whilst this imbalance exists at nearly all levels, it is particularly noticeable at senior levels. Incidentally, the Working Party has no explanations for the noticeable increase, albeit only to the ratio 1 : 4, of women permanent academic staff in the under 45 age group other than to muse that the changes in society must have had some effect on the profession. In Sections 4.3 and 4.4, we present data on the number of honours and PhD graduates in the mathematical sciences in Australia from 1959-92, and then specifically for 1993. The gender distribution is summarised in Table 4.2. We surveyed academic mathematical sciences departments in Australia and found that 77% of current PhD students were male. Anecdotally, we found that the gender imbalance also persisted in other institutions carrying out mathematical sciences research and supplying advanced mathematical services. On a broader front, the 1995 ARC Postdoctoral Research Fellowships were allocated 35 to males and 15 to females.

Table 4.2: Gender distribution for honours and PhD graduates in the mathematical sciences in Australia from 1959-92 and for 1993.

| | total number | percentage of males |
|---|---|---|
| honours graduates 1959-92 | 4272 | 79% |
| PhD graduates 1959-92 | 986 | 90% |
| honours graduates 1993 | 190 | 60% |
| PhD graduates 1993 | 21 | 86% |

It is clear that the gender imbalance in the mathematical sciences is deeply entrenched and becomes more pronounced with increasing years of study. The imbalance might be a little less pronounced than a few decades ago, but it appears to be more pronounced than in science in general, and is definitely more pronounced than in professions such as law, dentistry and medicine. In short, the mathematical sciences remain a male-dominated profession even at the levels where intake to professional ranks takes place.

In submissions to the review, it was pointed out that talented female students opt out of the mathematical sciences at decisive stages:

- on entry to university – when peer pressure is important and the mathematical sciences are perceived as not interesting enough in comparison to other courses
- on entry to postgraduate level – when it becomes clear that extensive further study is required and that career prospects are uncertain
- on entry to postdoctoral level – when doubts arise again about career prospects (not unreasonably, given the general discussion in the previous Section)

Of course, many students opt out of serious study of the mathematical sciences before they reach the universities. Moreover, the way that the discipline is presented is believed to encourage the average male more than the average female students. Given the predominantly masculine teaching staff in mathematical sciences departments, it is likely that males benefit more than females from the mentoring that is an essential part of academic apprenticeship.

In submissions to the review, university staff did not feel comfortable with affirmative action, in the sense of a quota at the time of employment, to increase the number of female mathematical scientists. On the other hand there was general agreement that more could be done to encourage talented female students to continue with their studies, and to retain these students once they were employed. An important aspect of this mission is the need to modify the expectations of parents for their daughters. Our suggestions are expressed in the following recommendation.

**Recommendation 8a**

☐ Professional societies, academic departments and employers of mathematical sciences graduates are encouraged to promote activities, aimed at senior high school students and senior undergraduates, which demonstrate career opportunities for talented female mathematical sciences students and which encourage them to continue to further studies.

**[Heads of Department, Professional Societies]**

**Recommendation 8b**

- ☐ The ARC is encouraged to award a special two year postdoctoral award to provide a role model for female mathematical scientists. The award, which would need to be appropriately publicised, might be called the Hanna Neumann Postdoctoral Fellowship.

**[ARC]**[38]

**Recommendation 8c**

- ☐ Employers are encouraged to provide flexible arrangements so that female researchers at postdoctoral or junior academic level can continue their careers after breaks for child-rearing.

**[ARC, AVCC]**

We note that activities encouraged by Recommendation 8a are extremely important, irrespective of the emphasis on female students.

## 4.3 Number of Honours Graduates

We are fortunate that there is excellent data[39] for the number of honours graduates in the mathematical sciences in Australia. This information, presented in Figure 4.1, is for all institutions accepted as universities by the Australian Vice-Chancellors' Committee.

Other data provided by Petocz shows that the total number of honours graduates in the mathematical sciences in Australia between 1959 and 1992 was 4,272, of which 79% were males. The universities with the largest numbers of honours graduates were Monash (718), Adelaide (598), Sydney (486), Melbourne (471), Queensland (262), New South Wales (258), Western Australia (253), ANU (250) and La Trobe (220). The number of honours graduates was high in the 1970s, but then fell back substantially during the 1980s, possibly as students reacted to feedback about career prospects in the universities (as described in Chapter 2). There has been an upwards trend in the number of honours graduates during the last 10 years, perhaps helped by a recession in Australia and diminished general employment opportunities that made another year of study more attractive to students.

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[38]Hanna Neumann was Australia's first woman professor of mathematics and the only woman mathematician ever elected to Fellowship of the Australian Academy of Science. In 1964 she accepted an invitation to take the newly created chair of pure mathematics at the Australian National University where she designed new honours courses, supervised graduate students, created a supportive environment for her staff, and carried out distinguished work in the theory of groups.

[39]Submission by Dr P Petocz, University of Technology, Sydney.

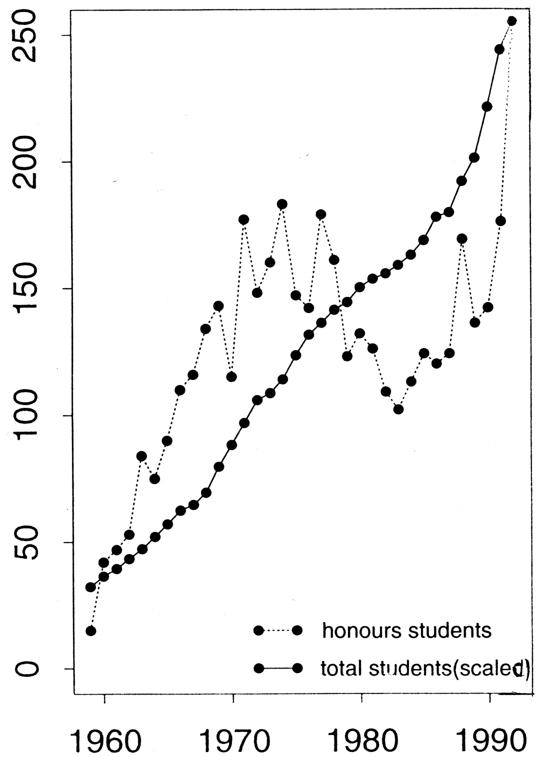


Figure 4.1: Honours bachelors degrees in mathematics and statistics in Australia, 1959-1992. The total number of students in higher education in 1992 was 559,365; this has been scaled to correspond to the maximum number of honours degrees.

The above information can be supplemented by more detailed information for 1993[40] presented in Table 4.3. The gender balance is noteworthy, particularly the number of female honours graduates in statistics. The total number of honours graduates in 1993 is 190, consisting of 114 males and 76 females. This total is the second highest ever, but 25% down on the 1992 total of 255.

Table 4.3: Honours graduates in the mathematical sciences, 1993.

| field | | I | IIA | IIB | III |
|---|---|---|---|---|---|
| mathematics & computing | M | 7 | 6 | 5 | 2 |
| | F | 5 | 3 | 0 | 0 |
| mathematics | M | 1 | 0 | 0 | 0 |
| | F | 0 | 0 | 1 | 0 |
| pure mathematics | M | 25 | 8 | 2 | 0 |
| | F | 9 | 5 | 2 | 0 |
| applied mathematics | M | 25 | 6 | 4 | 0 |
| | F | 4 | 7 | 2 | 0 |
| statistics | M | 12 | 15 | 5 | 1 |
| | F | 10 | 22 | 6 | 0 |

[40]ibid.

## 4.4 Number of PhDs

Information about the number of PhD students in the mathematical sciences – past, present and future – was obtained by submission (Petocz[41]) and by surveying departments. Historical information presented in Figure 4.2 shows the number of PhDs, the number of MSc degrees by research, and the total number of students in higher education. In all, 986 (90% male) PhDs had been awarded in the mathematical sciences in Australia up to 1992. For 30 years, the number of PhD graduates has fluctuated around 30-35 per annum. The figures for 1993 were 21 graduates (18 male, 3 female). This is the lowest for 25 years.

The universities with the largest number of PhD graduates in the mathematical sciences from 1959-92 are ANU (188), Monash (150), Adelaide (115), NSW (108), Sydney (74), Melbourne (60), Queensland (59), Flinders (43), Western Australia (36), La Trobe (35) and Newcastle (34).

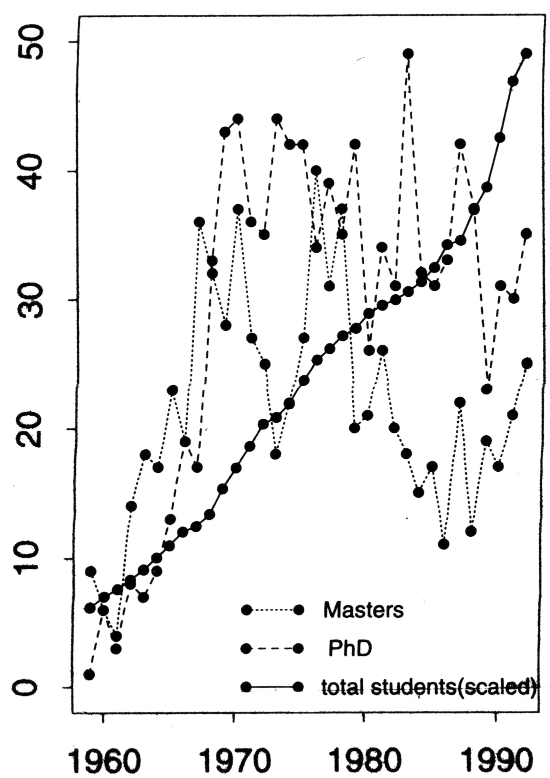


Figure 4.2: PhD and research MSc degrees in mathematics and statistics in Australia, 1959-92.

[41] ibid.

Surveys of mathematics sciences departments show that the number of PhD enrolments has increased sharply since 1989, and that further increases are expected during the 10-15 year horizon of this review. The information in Table 4.4 was compiled from a questionnaire distributed to all academic mathematical sciences departments in Australia. An important reason for an expected increase in the number of PhD graduates is the introduction of the unified national system in the late 1980s. At present many staff members in the new universities are studying part time for a PhD. Also, these new universities will themselves seek to attract graduate students to enrich their activities. It is also noticeable that it is becoming more common in mathematical sciences departments to have teams of researchers including postgraduate students supported by ARC grants. Lastly we expect a modest increase in the number of PhD students sponsored by government laboratories (CSIRO, DSTO, *etc.*) and industry.

Table 4.4: Full-time and part-time PhD enrolments in academic mathematical sciences departments in Australia.

| full-time | | | part-time | | |
|---|---|---|---|---|---|
| 1989 | 1994 | 2004 | 1989 | 1994 | 2004 |
| 126 | 378 | 585 | 48 | 120 | 168 |

[Data gathered by questionnaire; figures for 2004 are estimates; survey covers about 95% of academic mathematical sciences departments.]

The number of PhD enrolments in Australia is considered again in Chapter 7 where it is noted that there has historically been a low number of PhD graduates produced by mathematical sciences departments in Australia in comparison with overseas departments and with other disciplines in Australia. Thus the sharp increase in the number of students described in Table 4.4 can be seen as a correction to previously anomalous behaviour rather than as exceptional in itself.

Departments were also surveyed to identify the gender balance of current PhD students. Unfortunately, this survey had only[42] a 65% response rate. The results suggest that 23% of current PhD students are female.

[42]Most of our university data comes from near 100% response rates.

## 4.5 Career Structure for Postdoctoral Fellows and Junior Researchers

One significant concern identified during the review was the necessity for postdoctoral fellows and junior researchers to feel they have a viable career path to follow. The problem with the career structure is that there are so few tenured positions available in the system.

There is however a substantial number of short term postdoctoral positions in mathematical sciences departments in Australia. According to data gathered during the review, there are 113 such positions filled at the moment. These researchers include postdoctoral fellows, on ARC funds for example, as well as postdoctoral research assistants perhaps funded by non-ARC sources. The figure of 113 postdoctoral researchers was obtained from a near 100% response rate to our query, but it does include fractional and very short term appointments.

Of the 113 postdoctoral researchers, 77 are supported by ARC funds, 10 by CRC funds, 16 by university funds, 3 by industry and 7 by other mechanisms. Only 11% of the postdoctoral researchers are female.

Given the present age distribution of staff in mathematical sciences departments and the substantial number of postdoctoral appointments, it is inevitable that many people must drop out of mathematical sciences research at the end of a succession of postdoctoral positions. The Working Party considers it is particularly wasteful to have people who have spent perhaps ten years of their careers in postdoctoral positions, but who are unable to obtain a position which allows them to make use of the skills they have developed. We have already discussed in Section 4.1 how the lack of appointment opportunities for postdoctoral level researchers is a problem for the mathematical sciences in Australia. The above discussion reinforces Recommendations 7 (concerned with the age structure of mathematical sciences departments) and 17 (concerned with the need to broaden the funding base for the profession).

## 4.6 Immigrant Researchers

Historically, Australia has always relied on other countries to provide a significant proportion of its researchers and academics in the mathematical sciences. Many professors in our universities received their postgraduate education in England or the United States, and, up until the mid 1980s, appointment of Chinese, Indian or British citizens as researchers was common.

Former Soviet researchers have entered Australia in large numbers, although they have not yet been extensively incorporated into the academic, government or private workforce because of limited appointment opportunities. Instead, they occupy short term or part time positions as they become available. These researchers tend to have very strong classical training, extensive publication lists, but relatively weak computer skills in comparison with their Australian counterparts. This influx of researchers is a one-off phenomenon whose influence may last over the horizon of this review, but which will abate over the next few years.

Australia is undoubtedly enriched by this influx of immigrant researchers. It is, however, too much to expect them to be immediately employable in Australia even if positions were available which is not generally the case. Their relative lack of computer skills is one deterrent to appointment, as is the lack of fluency in English as required for lecturing or employment in government laboratories or industry. The development of specific courses for overseas trained professionals that address English for professional purposes, enhance computer skills and have work placements to ensure understanding of Australian business culture is essential if the skills of these immigrants are to be fully utilised. Such courses have been funded by DEET in recent years at a number of tertiary institutions *e.g.* University of Wollongong, RMIT and Victoria University of Technology.

Lastly, it would be unwise for Australia to rely on immigrant researchers to meet any shortfall in its human resource requirements at PhD level for the mathematical sciences. To obtain internationally trained specialists, Australia generally has to offer internationally competitive salaries, and this has become ever harder to do over the past 20 years. Anecdotal evidence suggests that Australian salaries are significantly behind those in the USA and Germany, and instances of recruitment difficulties in rapidly developing fields (particularly operations research and image analysis) were reported to the Working Party on a number of occasions.

# 5

# Educational Issues

## 5.1 The PhD degree

Various aspects of the PhD degree in the mathematical sciences in Australia are described elsewhere in this report. Section 4.4 considers the number of PhD graduates over the past 30 years and suggests that these figures are expected to continue increasing during the term of this review. That section includes a brief mention of the impact of the former Colleges of Advanced Education into the unified national system of universities. In Chapter 7, the funding of PhD studies is investigated, and it is also pointed out that PhD students play a significant role in the nation's research effort in the mathematical sciences. For reasons given in that Section, the contribution of PhD students to the nation's research output in the mathematical sciences is expected to increase sharply.

Two significant qualitative factors associated with the PhD degree in the mathematical sciences in Australia are considered here, namely the nature of the output and that, other than for those who travel overseas, Australian PhD students to a very large extent undertake their PhD studies in the same university in which they took their undergraduate course. This lack of mobility means that Australian PhD graduates do not have as wide a range of experience as their overseas counterparts.

Many submissions to the review touched on the fact that PhD students run the risk of being 'clones' of their supervisors, with research interests and career development that replicate their supervisor's. One detailed submission called for a new sort of PhD that would be more useful to the needs of Australian industry[43], and several participants in panel discussions expressed their difficulty in recruiting employees from amongst the crop of available PhD graduates. These observations suggest that prospective employers are uneasy about employing a PhD graduate for anything other than work in the specialist area of the thesis topic. This view is encapsulated thus: "Though admirable by traditional criteria, as far as the requirements of industry, the present PhD format errs on the side of specialism and so does not develop powers of synthesis and judgement over a broad field."[44]

[43] "The PhD education of mathematicians for industry: new responsibilities of universities", Dr J G Sekhon, personal submission to the review.

[44] ibid.

As we discussed in Section 3.6, a mechanism exists — namely the Australian Postgraduate Award (Industry) — by which students can undertake a PhD with immediately applicable content. These awards require an industrial partner who provides modest cash and in-kind support to supplement the APA(I) grant from the ARC. As yet, the involvement of mathematical sciences PhD students in this scheme is almost negligible. One would wish to see the scheme used and tested by mathematical sciences postgraduates before introducing yet another funding scheme or introducing a new sort of PhD.

The above discussion is an Australian reflection of a major US study[45] which expresses concern "about whether the needs of the profession and of an increasingly technological society are being met. Many doctoral students are not prepared to meet undergraduate teaching needs, establish productive research careers, or apply what they have learned in business and industry. This inadequate preparation, continuing high attrition ... the inadequate interest of women students ... are problems that transcend the current difficult job market."[46]

Annually, the USA produces some 30 times as many PhD graduates as are produced in Australia; its graduates undoubtedly span a broader range of specialities and educational styles than do Australian graduates. Australian mathematical sciences PhDs rarely have a formal coursework component, whilst US PhDs commence with several years of coursework (however our honours year goes close to providing the first year of such work). Nonetheless, it is worthwhile to describe the main findings of the cited US National Research Council report on PhDs since we feel these findings will have increasing relevance to the Australian context over the horizon of this review. The NRC report found that there are several different models for PhD programs, including:

- the standard model, which supports research in a broad range of areas, offers depth in each one, and has as its goal preparation for careers at research universities, and
- specialised models, such as the subdisciplinary model, the interdisciplinary model, the problem-based model, and the college-teachers model, which were seen to alleviate two large human resource problems, recruitment and placement, and to be conducive to clustering of faculty, postdoctoral associates, and students, a practice that helps create a positive learning environment and promote relevant professional development.[47]

[45] "Educating mathematical scientists: doctoral study and the postdoctoral experience in the United States", National Research Council, Washington DC, 1992.

[46] ibid., p.1.

[47] ibid., p.2.

We do not feel it appropriate to make specific recommendations about the style of PhD research in the mathematical sciences in Australia, and confine ourselves to a few observations. There is unease about the output of the nation's PhD students, and supervisor cloning is recognised as a risk even within the best departments in the country. There is almost no participation by mathematical sciences postgraduates in the APA(I) scheme. Compared to other disciplines in Australia and with other mathematical sciences departments overseas, Australian mathematical sciences departments support perhaps only some 50% of the PhD students that might be expected. (See Chapter 7 for more details.) Our surveys did however indicate that all departments intend to significantly increase their number of PhD students over the next decade.

The NRC report points out unequivocally that specialised PhD programs offer many benefits to students. In addition, our country has a small population which is widely dispersed. It is difficult to carry out excellent research on a broad front at more than a handful of university departments. For the remaining departments, it makes good sense to concentrate on just one or a few areas; the NRC report shows how this can be done. A more focussed approach to PhD supervision contributes to a sense of teamwork, helps to develop a positive learning environment, and will make it easier to recruit and fund further students. If that approach is adopted, then it is likely that the leakage of mathematical sciences graduates to other disciplines can be halted thus contributing to the long term benefit of the profession.

We consider it would be valuable for departments to obtain and study the NRC report cited earlier. As appropriate, it will be useful for PhD programs to be modified so that the overall cohort of PhD graduates will be better able to communicate with users of the mathematical sciences, will be better suited to the general technological needs of the country, will be more likely to find employment outside the universities, and will be funded by a broader spread of sources than at present.

We now consider the particular feature of the immobility of Australian researchers in the mathematical sciences. This mobility between institutions is low by international standards, even allowing for the fact that Australia is a large, sparsely populated country with a handful of widely separated cities on the seaboard.

The low mobility of postgraduates is not confined to the mathematical sciences. Out of the 1199 new Australian Postgraduate Awards in 1992, fully 871 were awarded for study in the same institution as that in which the recipient was an undergraduate. The corresponding figures for 1993 were 917 out of 1375.[48] This mobility, or lack of it, was the

[48] ARC Report on Research Funding Programs 1993 (Table 6), 1994 (Table 7.1).

subject of an in-depth study in 1992[49] which eventually recommended that barriers to mobility of postgraduate students should be reduced: "The Government and institutions should provide additional incentives, including conference allowances, additional relocation support or other support services, to promote mobility between institutions".

Submissions to our review saw benefits in greater mobility between institutions of mathematical sciences postgraduates. There was an even stronger feeling that mobility was important for postdoctoral fellows. Overall, increased mobility would improve the skills base, awareness and knowledge in the profession. We therefore urge the introduction of mechanisms to improve the mobility of junior researchers. We also urge the use of available technology to promote wider awareness throughout Australia of the research interests and supervision capabilities of the various mathematical sciences departments. We acknowledge that there is already some implementation of the following recommendation:

**Recommendation 9a**

☐ Financial disincentives to mobility between institutions of postgraduates and postdoctoral fellows should be removed by provision of increased removal and travel allowances, and in other ways to be identified. Mathematical sciences departments should actively recruit postgraduates and postdoctoral fellows from other institutions.

[**ARC, Heads of Department**]

**Recommendation 9b**

☐ The professional societies are encouraged to facilitate access to information from university departments concerning possible PhD topics and supervision arrangements. Departments are encouraged to maintain such information on their World Wide Web pages, and the societies through their own WWW server should provide easy links to those pages and should publicise that fact.

[**Professional Societies, Heads of Department**]

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[49] *Postgraduate student support and student mobility*, ARC Working Party Report, September 1992.

## 5.2 The Master's Degree

Data gathered by Petocz[50] shows that about 20 research master's degrees in the mathematical sciences were awarded annually in the late 60s, that this number had grown to about 30 annually by the late 70s, and then fallen back to about 15 annually by the late 80s. (Figure 4.2 displays this data.) Data is not available for the number of master's degrees by coursework, but our belief is that the number has never been particularly high.

There is now, however, evidence of need for a structural change in the master's degree in the mathematical sciences in Australia:

- For graduates to play a successful role in industry and the community, a portfolio of additional skills is required: teamwork, communication, problem-solving for practical purposes, experience in modelling, computing and general employment experience. The master's level course or the postgraduate diploma provides the opportunity for graduates to acquire such a broader set of skills.
- All professionals need to commit themselves to a paradigm of lifelong learning and updating of skills. Continuing study should be given proper recognition and reward in accreditation. In this, master's level courses can play a major role.
- Many of the newer universities in the unified national system have introduced or intend to introduce master's degrees by coursework. These courses provide a wider choice for Australian students, and provide access for overseas students, particularly from SE Asia where the demand for education sometimes cannot be met by existing local institutions. The viability of these new offerings is assisted by the opportunity to charge full fees.

Our survey of mathematical sciences departments in Australia showed that most universities offer master's degrees both by coursework (perhaps with a minor thesis component) and by research thesis. Overall, a strong growth in enrolment is expected for both sorts of degree, with a total of some 600 expected to be enrolled in MSc courses in the mathematical sciences in 2004.

[50] P Petocz, "Higher degrees in mathematics and statistics completed in Australia 1988", *Austral. Math. Soc. Gazette* 17 (1990), 125–131.

Table 5.1: Total enrolments in master's courses in the mathematical sciences in Australia.

| thesis | | | coursework | | |
|---|---|---|---|---|---|
| 1989 | 1994 | 2004 | 1989 | 1994 | 2004 |
| 106 | 185 | 269 | 86 | 170 | 318 |

[Data obtained from survey of departments.]

Most universities still have modest enrolments in their master's courses, but exceptions are already clearly observable. The University of Sydney has vigorous master's programs of both types. Monash University specialises in research master's, often as a preliminary step before PhD enrolment. Meanwhile, universities such as the Queensland Institute of Technology and the University of South Australia both intend to develop substantial enrolments in their coursework master's.

To gain an international perspective, we refer to an in-depth study in the USA by Friedman & Lavery[51], particularly their section on master's programs in industrial mathematics. In their words: "While industry needs all levels of expertise in the mathematical sciences — bachelor's, master's, doctoral, postdoctoral and research — one message that comes through in conversations with mathematical scientists and managers in industry is that the master's level is often a preferred level. A person with a master's degree is an excellent choice in many industrial projects, where compromises between breadth and depth and between level of expertise and length of study have to be considered. The master's degree has traditionally been a standard degree for industrial practitioners in statistics and operations research. In Europe, degrees such as the *Diplom* in Germany and the *diplôme* in France, which are equivalent to the master's degree, are professionally recognised stopping points for industrial practitioners in all areas of the mathematical sciences."[52]

Given the above comments, one would expect significant change in master's programs in Australia. We ascribe the previous low number of master's graduates in the mathematical sciences in Australia to (i) the relative immaturity of industrial needs and (ii) academic encouragement of talented students to undertake PhD studies immediately as an alternative to the master's degree. Emphasis on research master's rather than coursework master's parallels the previous low emphasis on technology transfer in Australia and our academics' previous emphasis on basic research.

[51] Avner Friedman and John Lavery, "How to start an industrial mathematics program in the university", Society for Industrial and Applied Mathematics, Philadelphia, 1993.

[52] ibid., p. 15.

It is worthwhile to make a comparison of Tables 4.4 and 5.1. The first shows that the total number of PhD enrolments expected in the mathematical sciences in 2004 is about 750, whilst the second shows total expected enrolment in master's courses in 2004 is some 600. These figures represent a mixture of estimates and hopeful guesses, but they do embody expectations about the nature of the mathematical sciences in Australia in ten years time. The number of PhD students would appear to be too high, whilst the number of master's students would appear to be too low. Based on overseas activities at master's levels, we would expect (i) the number of master's graduates will increase over the 10–15 year horizon of this review, and (ii) significantly more master's graduates (including those by coursework) will be produced than PhD graduates.

The Working Party considers it is appropriate to make the following recommendation about master's programs in the mathematical sciences in Australia.

**Recommendation 10**

- ☐ Departments are encouraged to carry out market research aimed at establishing master's level courses which will meet the needs of Australian industry. These courses should embody necessary mathematical, statistical and computational knowledge, communication skills, management methods, industrial placements and project work. As appropriate, these courses should be established.

[**AVCC, Deans, Heads of Department**]

The above comments (particularly on the balance between PhD and master's students) and the reference by Friedman & Lavery are also offered as suggestions for department heads to consider and adopt if appropriate to their needs. As suitable, department heads might wish to collaborate with colleagues in nearby universities in funding market surveys. Changes to the number of PhD and master's students are likely to be driven by funding exigencies; in that sense, it is not unreasonable to expect that departments will increase their number of fee-paying master's students, particularly those by coursework.

## 5.3 Undergraduate Initiatives

Collectively, mathematical sciences departments have a number of major roles to play in undergraduate teaching. The most important of these is to impart a grasp of the principles of university level mathematics, thus providing the foundation for more specific activities such as education of mathematical sciences majors, service teaching, and preparation of undergraduates for applications-oriented work in their subsequent professional lives. The undergraduate years also provide a testing ground by which the most able students can be identified and groomed for future research careers.

The precise balance between these various roles depends on many factors, such as the research capability of the department, its funding opportunities, and where the department and its university seek to position themselves in the spectrum between basic research and applications. Australia has more than 40 academic mathematical sciences departments, and there is a healthy diversity in their roles in undergraduate teaching.

The comment perhaps most commonly received by the Working Party in carrying out this review is that there is a real decline in the standard of high school mathematics. This matter is addressed in the next section. If true, this has the consequence that undergraduates require more introductory material than previously and that departments will have difficulty in producing suitably trained graduates in the standard three years currently allowed for a bachelor degree.

Service teaching in undergraduate mathematics deserves serious consideration in this Review. This topic is enmeshed with funding of mathematical sciences departments and a detailed discussion appears in Chapter 7.

The Working Party identified initiatives in many universities designed to improve teaching in the mathematical sciences. Student evaluation of courses and teaching is now standard practice in many departments. In addition a number of other projects were identified, often in conjunction with mathematics education researchers not located within the mathematics department, with a focus on improving the appropriateness of courses and course delivery. These included

- special course arrangements and mentoring for talented students (for example at UNSW and at Macquarie University)

- intake testing, for example at the University of Melbourne, and counselling of students to ensure appropriate course choice

- a number of CAUT (Committee for the Advancement of University Teaching) projects around Australia, many with an emphasis on incorporation of computer algebra systems into teaching in the mathematical sciences

- improved access to computer laboratories, and their use in teaching in the mathematical sciences

- a postdoctoral fellowship in the La Trobe University Graduate School of Education to explore the factors which might influence students' decisions to pursue mathematics over the three years of study in Victorian tertiary institutions
- a PhD study into factors affecting non-English speaking background students' participation in mathematics at tertiary level
- the development of the Bridging Mathematics Network which has met annually since 1991 and which has considered, in particular, the teaching of mathematics to students with special needs in tertiary settings, including Aboriginals and Torres Strait Islanders

The activity in mathematics education research in tertiary settings is such that a special seminar will be held in Auckland in 1997 when members of MERGA, AustMS, NZMS and the Bridging Mathematics Network all have conferences planned in New Zealand. The seminar will address a number of issues which will be important in the future, especially relating to gender issues, and equity issues and computers.

The Working Party was keen to hear about exciting new initiatives in undergraduate education in the mathematical sciences insofar as they related to the provision of advanced mathematical services. Accordingly, academic departments were surveyed to ascertain what specific measures had been introduced to train undergraduates to provide such services. Some half of the respondents chose not to answer this question — perhaps indicative of dissatisfaction with our emphasis on advanced mathematical services — whilst the rest gave a variety of answers. Favoured mechanisms include introduction of joint degrees (*e.g.* double majors in mathematics and finance, mathematics and electrical engineering, mathematics and ecology), inclusion of undergraduate units focussing on applications and computer simulations (operations research, computational mathematics, statistics including Total Quality Management), introduction of courses in mathematical modelling, and, in a few cases, introduction of courses in oral and written communications skills. An overall emphasis on involvement of industrial users in undergraduate programs was visible.

Lastly, we touch on the role that information technology developments will have on undergraduate teaching in the mathematical sciences. This influence will be significant; it will include provision of better education at a distance, the incorporation of teleconferencing so as to share specialist courses, widespread use of computer hardware and software, and widespread use of multi-media material in lecturing. These themes are explored in Chapter 6. The overall result will be improved undergraduate teaching with a broader diversity than exists at present.

## 5.4 K-12 Teaching of the Mathematical Sciences[53]

In recent years, there has been a vigorous debate in Australia about the teaching of mathematics to school children. In its specific aspects, this topic is outside the Terms of Reference of this review, but it nonetheless formed the basis of many submissions. Viewed from a broad perspective, it is clear that there is a strong and continuing need for an excellent educational base in the mathematical sciences.

In its submission to the review, the Australian Mathematical Society alluded to the "reduction in time devoted to mathematics in some school systems", with "deleterious effect on future mathematicians, scientists, engineers. ...students need both a facility in manipulation, which can only be obtained from sustained practice within an appropriate curriculum, and a standard of rigorous thinking which requires sufficient time to cultivate. To counter this problem it is necessary both to increase the overall time spent on mathematics in schools and to make special provision for highly talented mathematics students who will be the nation's future researchers and providers of advanced mathematical services".[54] To put the above comments in perspective: the number of students taking advanced level mathematics courses in the senior years has not increased (in some states, the numbers are falling), although there has been a large increase in retention rates. Also, intake testing and results at the University of Melbourne, for example, shows that the best students are very good but there also are many very poorly prepared students in the university system. Considerable improvement in school mathematics should be achievable.

Mathematics teaching at all levels needs careful instruction by skilled and committed educators. It is essential that initial and in-service teacher training be of high standard both in discipline knowledge and in teaching and learning skills. Mathematics courses, particularly in years 11 and 12, should be taught only by teachers who have a university major or a higher degree in mathematics. The minimum standard for teacher training for mathematics teachers at all levels should be that established by the Speedy Report.[55]

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[53]Most of this Section is based on a detailed submission by the Australian Mathematical Sciences Council, a peak body representing researchers, mathematics education researchers and school mathematics teachers.

[54]Extract from submission of the standing Committee on Education of the Australian Mathematical Society.

[55]*Discipline review of teacher education in mathematics and science*, Department of Employment, Education and Training (Australian Government Publishing Service, Canberra, 1989).

The mathematical sciences occupy a central place in the scientific and general well-being of the nation. Thus there ought to be proper reward for those who choose to pursue a career in mathematics teaching. Unfortunately, salaries and conditions in schools are much less attractive than in the past, and the matriculation scores of entrants to teaching are significantly lower than they are for many other professions. This is a serious problem for the education system, particularly so for mathematics and science. Differential salary rates should be available for teachers who have appropriate higher level qualifications and expertise in their learning area. In addition, other incentives such as paid study leave and opportunities to work in industry, such as is provided by the Teacher Release to Industry Program (TRIP) scheme in Victoria, should be generally available.

In recent years, school mathematics has been expected to take account of greater understanding of how students learn, the changing demands of the workplace, the impact of technology, and many more students completing 12 years of schooling. This is occurring at a time of reduced resources for curriculum development and for appropriate professional development for teachers, particularly at State level. *A National Statement on Mathematics for Australian Schools* was a timely development that was worthy of support but the process used in its development has correctly been criticised for not involving many key people. The Statement was subsequently reviewed under the auspices of the Australian Association of Mathematics Teachers but the many recommendations of that review have still to be implemented in any systematic way.

The subsequent development of *Mathematics: A Curriculum Profile for Australian Schools* has been controversial. The document is not acceptable to most mathematicians and a number of mathematics educators have serious reservations about its rationale and research base. A number of reviews of varying depth and with various terms of reference have occurred around Australia. There appears to be little co-ordination of this work. At the same time, whole cohort testing introduced in a number of states does not appear to represent best practice in assessment. The need for accountability is accepted, but if school mathematics in Australia is to be both world-standard and meet national needs and equity objectives, there needs to be a sensible rationale for the teaching and learning of mathematics in schools and appropriate assessment developed collaboratively by the key players, especially teachers.

Australia is currently participating in the *Third International Mathematics and Science Study (TIMSS)*. More than 50 educational systems are involved in a project that will report comparative data covering content and other aspects of the mathematics curriculum over several years. TIMSS will provide international comparisons for school mathematics in Australia. The data will need to be carefully analysed to ensure that effective initiatives are undertaken to ensure Australian students are achieving at appropriate levels compared with other nations. It should be noted that OECD figures indicate that school expenditure per student relative to per capita GDP in Australia is low compared with many other industrialised nations and that any efforts to act on the TIMSS data will require an extra commitment of resources on the part of state and federal governments.

# 6

# Future Information Technology and Computing Developments

## 6.1 Introduction; Implications for R&D in the Mathematical Sciences

The growth in computing capability has several distinct implications for mathematical sciences research and the provision of advanced mathematical services. These relate to information dissemination and retrieval (discussed in Section 6.4 below), the role of computers in undergraduate teaching (Section 6.5), the development of new computer architectures and associated performance improvements, and the major effects of software developments on the style of research undertaken in various disciplines (Sections 6.2-3). The overall consequences for the mathematical sciences are a greatly enhanced capability for computational experimentation, increased research productivity, and significant and sometimes unpredictable changes to the discipline and associated disciplines.

In Box 6.1, we give an example of realistic three dimensional simulations of turbulent flow in complex geometries handled on today's desktop computers. Similar advances occur in many other areas: design of structures, drug design and numerical weather forecasts to name just a few. (We emphasise again that these computations are highly dependent on advanced mathematical concepts.) To the computer user and eventual customer, this means that better and more timely products and services are produced than previously used to be the case.

In fact, computation has become a scientific tool of the same level of importance as theory or experiment. To a mathematical sciences researcher working on basic research, the computer now gives new perspectives to existing results, enables a more complete understanding of current work, and opens up new fields for investigation. A typical example is the role of the computer in number theory, as described in Box 6.2. This pivotal role of the computer is very different to the situation of a generation ago when mathematical sciences researchers typically did not need major hardware or software to carry out their work.

Information technology developments contribute to the professionalism of the mathematical sciences at least as much as they do to other disciplines; indeed probably more, since preparation of mathematical manuscripts and books, once a highly technical skill, is now within the ready reach of anyone prepared to learn a simple and transparent computer language for the purpose.

The conclusion is clear: the mathematical sciences are now a laboratory-based subject. As such, they need to be funded appropriately. This leads to the following recommendation:

**Recommendation 11**

- ☐ Departments and universities should ensure that staff and students have access to appropriate computers, software, support staff and network connections. To support such infrastructure for advanced teaching, research and communications, mathematical sciences departments should be funded on a comparable basis to computer science departments.

[**DEET, AVCC, Deans**]

**Box 6.1 High performance computation**

Ten years ago in Australia, it was virtually impossible to carry out large numerical simulations of fluid flow in complex three dimensional geometries. The few computers in the country capable of addressing this task were based in central facilities and were far too expensive for routine use in industry. Moreover, off the shelf software to solve the problems was not available.

The cost/performance ratio of computers continues to fall rapidly, and now it is possible to buy a workstation with sufficient memory and processor speed to address large practical problems on a daily basis. In an example cited by CSIRO Division of Mathematics and Statistics, the three dimensional turbulent flow of molten steel in a tundish (like a big bathtub but with a more complicated shape), requiring more than 30,000 nodes in a finite element computational fluid dynamics (CFD) computation, was solved using less than 100 Mb of RAM on a desktop workstation within hours (and not days). It is not widely appreciated that the performance improvements are as much due to better algorithms as they are to hardware advances.

This sort of computing performance, which will certainly be seen as pedestrian over the horizon of this review, means that more realistic and more reliable simulations can be carried out on a routine basis. The consequence is that the computer will be more and more used as a design tool for CFD, for structural analysis, to design industrial equipment, to investigate the flow of granular material, and so on. Better products and processes will be the result, and these products and processes will get to market more quickly than used to be the case.

**Box 6.2 The role of the computer in number theory research**

Whilst the direct use of computers in the proof of Fermat's Last Theorem was only in typesetting the manuscript, computer experiments initiated by Birch and Swinnerton-Dyer at Cambridge in the 60s helped to provide the theoretical underpinning. In their work, computation transformed dubious hypotheses to near certain conjectures, both forming and refining expectations.

In a different direction, the *Riemann Hypothesis* claims that the non-trivial zeros of the function $\zeta(s) = \sum_{n=1}^{\infty} n^{-s}$ all have real part $\frac{1}{2}$. Supercomputer computations in Amsterdam have confirmed that the first 1.5 billion nontrivial zeros of the Riemann $\zeta$-function do indeed lie on the critical line. Apart from its contribution to theory, such work is valuable in confirming and refining multiprecision algorithms, parallelism and vectorisation techniques, and in testing the hardware integrity of computers. The notorious fault in the Pentium chip was discovered by similar testing.

In that spirit, it is commonplace for commercial supercomputers to be tested as part of their commissioning by running a multiprecision program extending the list of *Mersenne primes*, prime numbers of the shape $2^p - 1$. An amusing consequence is that in recent years major oil companies have held the record for discovering the largest known prime [currently $2^{859433} - 1$].

It is now possible to factorise numbers of some 130 digits, endangering some cryptographic methods in common commercial use. Most of the dramatic improvement in factorisation capabilities is due to algorithm refinements. In this field, computers have given rise to an entirely new subject, Computational Number Theory, a vigorous area at the interface of mathematics and computer science.

## 6.2 Hardware Developments

Computer hardware developments take place in many ways such as parallelism, miniaturisation, and development of chips with reduced instruction sets or compound operations (such as a combined multiply-add). There is fierce competition amongst computer vendors, and the cost:performance ratio of computers continues to fall inexorably. Box 6.1 gives an example of practical problems that can now be solved on typical workstation computers.

There is a natural limit — imposed by the speed of light in fact — for the speed of single processor computers. Massively parallel systems, with many relatively cheap processors connected in some way, avoid this constraint but strike another one — namely the need to communicate data from processor to processor. Automatic compilers exist that enable software to run on parallel systems, but, to get optimum performance, very carefully designed algorithms that minimise inter-processor communication are required. Thus a whole new research area has sprung up: development of algorithms for parallel architectures. This field is exceptionally vigorous at the moment. It relies critically on mathematical concepts.

The trend towards miniaturisation means that power that would once have been astonishing is available on notebook computers; there is currently no sign that the trend to increased performance is slowing. This contributes to the mobility of researchers, both within Australia and internationally.

An associated hardware issue is data acquisition. Nowadays, real time data acquisition is routine, and control and optimisation use the concept of real time control of systems based on data that depreciates in value over time. Large and complex data sets, often in the form of images, must be handled routinely. These data sets make their own demands on hardware systems for storage, analysis and display.

## 6.3 Software and Algorithm Developments

In the world of high technology computing it is easy to be seduced by hardware developments and overlook the role of software and the algorithms that underpin it. The continuous improvements in hardware performance are in fact matched by continuous improvements in algorithms. Perhaps the best known example is the Fast Fourier Transform described in Box 6.3, but similar performance improvements could be cited in dozens of other applications, with beneficial results across the whole spectrum of research and development. Algorithm improvements take many forms, including reduced operation counts, greater stability, better convergence properties, more accurate results for a given number of operations, and greater flexibility and robustness.

**Box 6.3 The Fast Fourier Transform**

The Fast Fourier Transform (FFT) refers to any one of a class of highly efficient algorithms for computing the complex Fourier coefficients

$$\hat{x}(\omega_m) = \sum_{n=0}^{N-1} x_n e^{2\pi i n m/N}$$

at $\omega_m = 2\pi m/N$ of a discrete time series $x_n,\ n = 0, \ldots, N-1$ where $N$ has many small factors. The FFT is commonly attributed to a famous paper by Cooley & Tukey in 1965. Fourier transforms are fundamental to many forms of signal and data analysis.

Naive calculation of the complex Fourier transform requires $N^2$ multiplications. However, if $N = 2^p$, Cooley & Tukey showed that the complete set of Fourier coefficients can be computed using $2pN = 2N\log_2 N$ multiplications. If $N = 1024 = 2^{10}$, then $2N\log_2 N = 20,480$ whilst $N^2 = 1,048,576$ which is more than 50 times as large.

Clearly, the FFT represents a huge improvement in efficiency over naive calculation methods. The advantages become even more pronounced as the number $N$ increases.

Algorithms need to be embodied in software, and it is here that there is the opportunity of commercial return. The major issues include the innovativeness of the developers, their commercial acumen, the size of the market, and the resources that can be assembled to develop the packages. It is not uncommon for hundreds of years of cumulative research effort to be invested in a major software package. Examples of major efforts to develop mathematical sciences software include symbolic manipulation packages (see Box 6.5 in a later section of this Chapter), optimisation packages of various forms (linear, nonlinear, integer, . . . ), statistical analysis packages (S-PLUS), and packages for graphics, matrix algebra and numerical solution of ordinary differential equations (IMSL, NAG). Graphics packages provide key benefits as explained in Box 6.4 and Figure 6.1. These mathematical sciences packages constitute a vigorous commercial activity; they provide tools that researchers need not develop themselves, and thus the packages can be considered as major agents for productivity improvement. They also change the style of work. More than ever, the single researcher has been replaced by a team of developers.

**Box 6.4 Display of quantitative information**

One of the liberations of the information technology age is the ability to display complex information and patterns in data.

This ability has generated new statistical research concerned with methods of display, and how displays influence the data analyst and the end-user of numerical information. Whilst in-depth data analysis can reveal simple information, the data analyst can often find simple graphs which reach the same conclusion. Graphs provide a supplementary technique to sophisticated analysis. It is an old aphorism that a picture is worth a thousand words — but a picture is also worth a substantial number of equations.

Graphs also play an essential role in checking the assumptions of models. Given data in the form of signal plus noise, graphical examination of the noise often indicates immediately whether the signal is a reasonable model. This is indicated in Figure 6.1 which is a display from a standard statistical package, MINITAB. Dynamic and interactive graphics enhance the process of building and understanding models. This area will see substantial development over the 10-15 year horizon of this review.

The mathematical sciences packages have as counterparts very large packages for particular applications in engineering and in the physical sciences. The mathematical component of these packages is usually well hidden but remains a critical determinant of success or failure. Examples include packages for computational fluid dynamics, structural analysis, drug design, tomography and weather prediction. These packages lead to an effect one might call the 'vanishing mathematician': the work of mathematicians of only a few years ago on applied problems is seemingly overtaken, and is incorporated into applications packages. In these areas the role of the mathematician as inventor, researcher and problem solver appears to disappear, to be replaced by the use of the mathematical concepts by engineers and scientists. The consequence for the mathematical sciences profession is that its former skills might appear superseded. The challenge is to display the new skills now required in collaborative work with other disciplines, for those disciplines have become capable of calling on yet more advanced mathematical notions.

Some see the potential for erosion of the mathematical sciences base by computer developments. But there is also a sense in which these developments have created a demand for a much higher level of mathematical skill. In the days when calculations had to be carried out by hand, the models and the methods of solution both had to be elementary. Now, however, the models and the approximation schemes can be enormously complicated, greatly increasing the possibility of imaginative forward leaps, on the one hand, and of disasters on the other hand, if the systems and approximation schemes are mishandled.

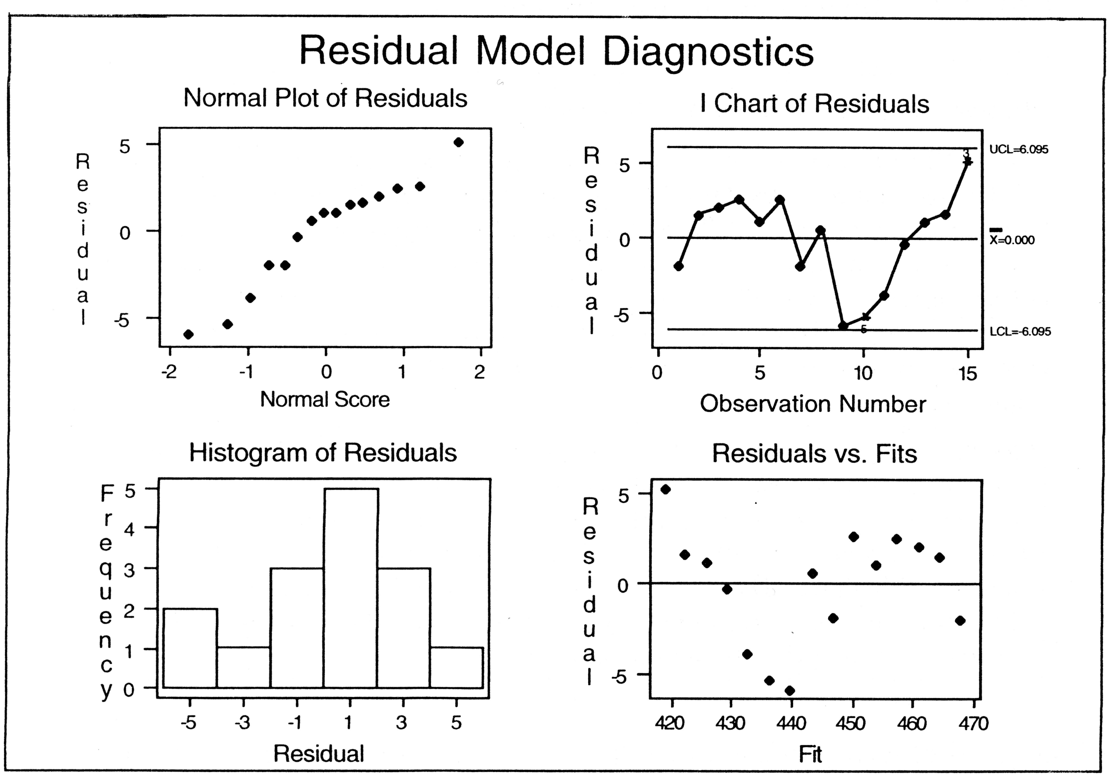


Figure 6.1: Graphical display of residuals for noisy data. The normal scores plot and the histogram give some evidence that the noise is not normally distributed. The I-chart of residuals shows some evidence of trends in time in the data. The plot of the residuals *versus* fits indicates that the model for the signal is not adequate. Such observations lead to improvements in modelling.

## 6.4 Libraries, Information Dissemination and Retrieval

Many submissions to this Review mentioned the high cost of library and information services to mathematical sciences departments and the declining ability of universities to maintain the range of necessary journals. The trends are well-known: journal charges increase at a rapid pace, exacerbated by depreciation of the Australian dollar, and there is a continuing stream of relevant new journals available to the professional. Small and new universities are particularly sensitive to these cost increases.

We received submissions which suggested that greater collaboration between universities in Australia could reduce the costs of maintaining good holdings of books and journals. This is because a rational collaborative acquisition policy would allow holdings to be cut nationally, whilst still enabling all Australian researchers to have reasonably quick access to reference material. Implementation of this policy would not be an easy task.

In our view the situation will alter dramatically during the next fifteen years. The current inability of libraries to maintain let alone expand their holdings will soon be irrelevant. Our views are influenced by a penetrating article by Odlyzko[56] who argues that the "growth of the scholarly literature, together with the rapidly increasing power and availability of electronic technology, are creating tremendous pressures for change." Odlyzko suggests that the impending change might well be abrupt, but will be accompanied by substantial increase in effectiveness of scholarly work and reductions in costs.

"The number of scientific papers published annually has been doubling every 10-15 years for the last two centuries. This is also true of mathematics alone. In 1870 there were only about 840 papers published in mathematics. Today, about 50,000 papers are published annually." Recently, "the number of [mathematical sciences] papers has been doubling about every 10 years."

"The exponential growth in mathematical publishing has interesting implications ... extrapolating from the current figure of about 50,000 papers per year and a doubling every 10 years, we come to the conclusion that about 1,000,000 mathematical papers have ever been published ... half of them in the last 10 years."

"A doubling of scholarly papers published each decade corresponds to an exponential growth rate of about 7% per year. This is fast, but

[56] Andrew M Odlyzko, "Tragic loss or good riddance? The impending demise of traditional scholarly journals", *Notices of the AMS*, 42 (1995), 49–53.

nowhere near as fast as the rate of growth in information processing and transmission. Microprocessors are currently doubling in speed every 18 months, corresponding to a growth rate of 60% per year. Similarly dramatic growth figures are valid for information storage and transmission." Odlyzko goes on to argue that typeset versions of a year's output of mathematical papers would occupy only some 2.5 GB of storage, an amount having almost nominal cost on read–only disks. All the papers ever published could be stored comfortably, using modern compression techniques, on less than 1,000 GB of storage which is large but manageable. In short, Odlyzko concludes that "electronic storage capacity needed for dissemination of [today's ] research results in mathematics is trivial with today's technology." He also discusses transmission capabilities and concludes that, in a decade, costs to transmit 50 GB of research papers in one's speciality will also be trivial.

Odlyzko describes one way that electronic publishing of scholarly papers might occur, not so much as to suggest this will be the unique version introduced, rather to point out the feasibility and benefits of electronic publishing. He goes on: "It is impossible to predict the date or speed of transition to systems like the one outlined ... but only because they will be determined primarily by sociological factors. The technology that is necessary for future systems is either already available or will be in a few years. ... Paper journals will have to convert to electronic publication or disappear. ... [Libraries] will have to shrink and change their role."

For libraries to shrink and change their role, a number of key issues will need to be resolved. These include the necessity for copyright laws to adapt to new technology. Also, there is a need for development of commercial aspects of publishing under the new technology: Who will pay for electronic access? How will publishers make a profit? Further requirements are new procedures for indexing, cataloguing, transmission of copies, and to ensure quality control of articles. These are formidable problems to overcome.

On balance, however, Odlyzko's case is compelling, and we expect that electronic publishing in forms similar to that he describes will be in place over the 10–15 year horizon of this review. Support for the swiftness of the change comes from considering the speed of development of the World Wide Web, now a commonplace tool for information dissemination. The WWW developed very quickly, within a couple of years, and this at a time when adequate tools to use and navigate the WWW are still under development. There are costs for misjudging the uptake of new technologies, but we repeat our view that the changes to electronic publishing will be swift, so that flexibility to adapt to the changes will be a benefit.

As Odlyzko points out, the rate-limiting factors in the introduction of electronic publishing and electronic libraries are sociological. What is critical is the body of professional opinion, shaped to a significant extent by professional societies and groups of researchers with similar interests. Change will undoubtedly come, it will probably be swift, and we feel that all participants should make whatever preparations they can for the change.

In this respect, it is encouraging to note that the professional societies are already making plans to exploit future information technology capabilities. The Australian Mathematical Society and the Statistical Society of Australia have set up electronic sites and are investigating electronic publishing of their journals. The Australian Society for Operations Research has established a WWW home page. Of course such services rely fundamentally on the quality of the underlying network.

With the above background, we make the following recommendation:

**Recommendation 12a**

- ☐ It is of utmost importance that networks be capable of handling the future challenges of the information age.

[**AVCC**]

**Recommendation 12b**

- ☐ Professional societies in the mathematical sciences are encouraged to continue their development of electronic operations. Mathematical sciences departments are encouraged to use the World Wide Web and its successors to promote their activities, to disseminate knowledge, and to increase the effectiveness of their teaching and research. Funding bodies such as the ARC are encouraged to provide funding to build up appropriate information technology infrastructure.

[**ARC, Professional Societies, Heads of Department, Deans**]

## 6.5 Undergraduate Teaching

Hardware and software developments mean that the mathematical sciences have become laboratory–based, and that computational science has become a third strand of scientific endeavour along with theory and experiment. Whilst this Review is concerned with mathematical sciences research and advanced mathematical services, it remains appropriate to consider implications of information technology developments on university teaching of mathematics.

Just as with electronic publishing and dissemination of knowledge, computer developments will have major ramifications on the way that the mathematical sciences are taught: for example, symbolic manipulation packages reduce the need for human involvement in algebraic manipulations (see Box 6.5), and packages enable routine solution of sets of ordinary differential equations. These two examples are by no means the only ones, and it is highly likely that information technology developments will cause major changes to professional mathematical activities and educational practices to take place over the 10-15 year horizon of this review. It is impossible to predict the full nature of the changes and their time of implementation, but awareness of the potential for change and flexibility to cope with new developments will be valuable. We also note that, while the above developments are to be welcomed, there remains a need for theoretical and practical underpinning of university education in the mathematical sciences. We therefore recommend as follows:

**Recommendation 13**

☐ Mathematical sciences departments are urged to survey their courses and re-design them to make best use of the growing power of computers.

[**Heads of Department, Deans**]

Traditionally, education in the mathematical sciences has been by ‘chalk and talk’ methods, usually in a lecture room with students at desks. This too is likely to change dramatically because of the possibility of information storage on disks and the growth of video conferencing capability. Instruction might well take place through use of a multi-media package, to be taken by students at their own convenience and generally not in a lecture room. On those occasions when real-time lectures occur, the material might be sent by video link to students at other campuses. There are obvious educational benefits to be claimed, both in efficiency and effectiveness.

Indeed, video conferencing in the mathematical sciences is already a reality in Australia — students in actuarial science at the Australian National University ‘sit in’ on lectures given at the University of Melbourne. Salary savings of academic staff are clearly achievable, at the expense of capital and running costs of the video equipment and connections, both of which will decrease over the 10–15 year horizon of this review. Further national and international sharing of courses and presentation of lectures by read-only disks are likely developments. There are implications for human resource requirements of universities with the potential to free staff for better course development and more individual student interaction. The greater opportunity for universities to carry out their research mission is evident.

**Box 6.5 Symbolic manipulation packages**

In the past several decades, powerful and creative packages have been developed which remove much of the drudgery out of *doing* mathematics. These packages include MAPLE, REDUCE, MACSYMA and Mathematica$^{TM}$. For example, Mathematica has a pronounced commercial and professional appearance, and has capabilities in the following areas: numerical calculations, graphics, algebra and calculus, solving equations, lists, matrices, transformation rules and definitions, symbolic computation and programming.

As a simple illustration of the capability of such packages, the following three lines of Mathematica

In[1] = 9(2+x)(x+y)+(x+y)ˆ2
In[2] = Expand [%ˆ3]
In[3] = Factor [%]

produce the output

`Out[1]` $= 9(2+x)(x+y)+(x+y)^2$
`Out[2]` $= 5832x^3 + 9720x^4 + 5400x^5 + 1000x^6 + 17496x^2y + 30132x^3y + 17280x^4y + 3300x^5y + 17496xy^2 + 32076x^2y^2 + 19494x^3y^2 + 3930x^4y^2 + 5832y^3 + 12636xy^3 + 8802x^2y^3 + 1991x^3y^3 + 972y^4 + 1242xy^4 + 393x^2y^4 + 54y^5 + 33xy^5 + y^6$
`Out[3]` $= (x+y)^3(18+10x+y)^3$

Mathematica has taken an algebraic expression, raised it to the third power, and has then correctly factorised the resultant complicated expression. The reduction in drudgery (and the increased time available for more creative work) is obvious. This does not however obviate the need for a thorough grounding in the conceptual understanding of the manipulations that are being carried out.

It is apparent that computer developments will have a profound effect on the way that university mathematics is taught in the future. Every student in the mathematical sciences will need a computer and appropriate network connections and software. A ‘universal acquisition’ policy will help departments cater for future needs of students in an efficient and equitable way. The following recommendation will assist these developments:

### Recommendation 14

- ☐ The government is encouraged to introduce a funding scheme (*e.g.* of HECS type or by way of low cost loans, and/or by sales tax exemption) by which all mathematical sciences students can readily acquire a suitable computer, software and modem connections. Universities and departments should support this recommendation by providing appropriate software and network connections, and by using bulk-buying power to obtain low prices for hardware and software.

**[DEET, AVCC, Deans, Heads of Department]**

Whilst we confine our recommendation to ‘mathematical sciences students’, it is easy to argue the case for computer availability for all students. Such arguments add to ours and improve the case for government assistance. We are aware that several universities already are considering introducing a requirement that *all* their students own or have access to computer and internet connections.

# 7

# Funding of Mathematical Sciences Research

## 7.1 Introduction

In this Chapter, we consider funding for mathematical sciences research. Essentially, this research is either pure basic or strategic basic research in the sense of Australian Standard Research Classification described in the footnote to Recommendation 1. Most of this research takes place in universities and most is funded by government, either as direct support for research (for example by the Australian Research Council) or as the research component of general operating grants given to higher education institutions. The other main component of general operating grants for universities is for teaching, and it is therefore clear that service teaching is a crucial feature of the work of mathematical sciences departments. The importance of service teaching is discussed in Section 7.4.

Funding for advanced mathematical services, or applied research and experimental development in the mathematical sciences according to the Standard Research Classification, occurs on a diversified basis. Here, the user or potential user of the research is much more likely to fund the work, and the levels of funding eventually depend on the success or otherwise of the activity. Funding sources include some government programs (for example those of DIST and part of CSIRO), particular government departments such as the Australian Bureau of Statistics, state government departments and private companies. In Chapter 3, we showed that there is scope for mathematical scientists to bid more vigorously for support through existing government programs. We also pointed out that there is a role for increased government involvement in infrastructure and technology transfer activities which support advanced mathematical services. Our views were captured in Recommendation 6.

In Section 7.2, we describe government funding for mathematical sciences research and show how this compares with funding for other disciplines. The role of the Australian Research Council is considered in Section 7.3, thus supplementing information provided in Chapter 2 about the ARC.

Table 7.1: R&D performance in higher education institutions by selected major fields of research, 1986-1992, figures in $ million.

| Field of research | 1986 | 1988 | 1990 | 1992 |
|---|---|---|---|---|
| Mathematical sciences | 21.9 | 29.8 | 32.7 | 45.1 |
| Physical sciences | 53.4 | 62.4 | 65.8 | 80.2 |
| Chemical sciences | 54.2 | 64.2 | 79.4 | 92.4 |
| Earth sciences | 48.8 | 53.5 | 69.4 | 76.3 |
| Information, computers & communication technologies | na | na | 48.9 | 74.9 |
| Applied sciences/technologies | na | na | 48.6 | 71.0 |
| Engineering | na | na | 90.3 | 115.8 |
| Biological sciences | 128.3 | 154.4 | 159.3 | 194.4 |
| Rural sciences | 58.0 | 66.4 | 83.7 | 97.2 |
| Medical & health sciences | 135.9 | 179.3 | 255.2 | 314.3 |
| Psychology | 25.0 | 23.4 | 28.2 | 36.3 |
| Education | 25.0 | 36.6 | 66.0 | 73.6 |
| Humanities | 102.2 | 124.7 | 119.2 | 163.2 |

## 7.2 Government Funding of R&D in the Mathematical Sciences

Table 7.1 displays R&D performance in higher education institutions by field of research[57]. This shows the level of funding for mathematical sciences research in comparison with other major fields, and it enables a prediction of trends. The data is for 1986, 1988, 1990 and 1992.

Table 7.1 shows that the mathematical sciences have a low level of funding in comparison with fields such as chemical sciences, biological sciences, and education. Given the central importance of the mathematical sciences as demonstrated in this report, there is a case for the mathematical sciences to claim a larger share of the resources described in Table 7.1[58]. For this to take place, however, we believe there would need to be a groundswell of support for the mathematical sciences, involving increased student enrolments, increased number of graduates, increased ARC support, perhaps the development of a better gender balance, and certainly increased community support brought about through more effective external communication.

Table 7.1 has the problem that the data is estimated by assuming that a given fraction of time of permanent staff is available for research. It

[57]Data from *Australian Science and Innovation Resources Brief 1994.*, Department of Industry, Science and Technology, Canberra, Table 5.3.

[58]For reasons given in Chapters 1 and 2, Table 7.1 does not record mathematical and statistical activity that takes place within other disciplines; but that does not materially diminish arguments for increased direct funding of the mathematical sciences as a vital central discipline.

would be better to look at direct government funding for research — a point made clearly in the footnotes to Table 6 in the 1995 Science and Technology Budget Statement. Unfortunately, comparative data between disciplines for direct government funding was not available. We therefore include Table 7.1, but with appropriate caution.

Table 7.2: 1990 R&D performance in the mathematical sciences in higher education institutions.

| sub-division | expenditure 1984$m | person years | academic staff | postgrad students | technicians | other staff |
|---|---|---|---|---|---|---|
| Pure math | 11.5 | 194 | 93 | 84 | 10 | 7 |
| Applied math | 10.0 | 212 | 84 | 95 | 21 | 11 |
| Statistics | 8.1 | 140 | 61 | 45 | 13 | 22 |
| Other math sci | 3.1 | 75 | 30 | 30 | 9 | 6 |
| All math sci | 32.7 | 621 | 268 | 254 | 53 | 45 |

The information in Table 7.1 for the mathematical sciences is dissected in Table 7.2[59]. Once again, the sub-fields are not those that we favour (see Recommendation 1). We stress that Tables 7.1 and 7.2 are concerned with research in universities, not teaching.

This table shows the important role of postgraduate research students in contributing to the nation's research, particularly in applied mathematics. In fact, however, postgraduate students contribute less on a proportional basis to mathematical sciences research than they do to other disciplines. To establish this, consider the ratio [number of postgraduate students]:[number of academic staff]. Table 7.2 shows this ratio for the mathematical sciences is 0.95 overall (pure mathematics: 0.90, applied mathematics: 1.13, statistics: 0.74, other: 1.00). Corresponding figures for selected other fields of research are[60] physical sciences: 1.59, chemical sciences: 1.89, earth sciences: 1.60, information technology, computers and communication technologies: 1.86, applied sciences and technologies: 2.39, engineering: 2.58, biological sciences: 1.97, and humanities: 2.03. Our anecdotal evidence is that this ratio for the mathematical sciences is lower than in major countries such as France and Germany. The conclusions are clear: *mathematical sciences researchers support significantly fewer postgraduate students than their colleagues in other disciplines.*

The reasons for this are uncertain – perhaps the nature of the mathematical sciences means that more supervision is required than in other disciplines; perhaps it reflects lack of vigour by academic mathematicians and statisticians; perhaps it reflects the assessment of

[59]ibid., table 5.4.

[60]ibid., table 5.4.

poor career prospects by potential PhD students, thus manifesting itself as a drift to other disciplines by PhD students. The narrow base of postgraduate funding in the mathematical sciences, with most postgraduate scholarships coming in the form of university APAs, is no help, given the more diverse sources found by other disciplines. In any case it does seem clear that more PhD students could undertake their studies in the mathematical sciences.

Another important issue is the level of funding support for various disciplines in the universities. Data available for the levels of support comes in four categories: capital works, equipment, salaries for support staff, and other current expenditure (notably consumables and services). Of these categories, the capital works data usually fluctuates widely from year to year and is therefore unreliable, whilst there is difficulty in comparing salaries of support staff with different salary structures. The other two categories of expenditure, which are argued to be more reliable, are displayed in Figure 7.1 for various disciplines[61].

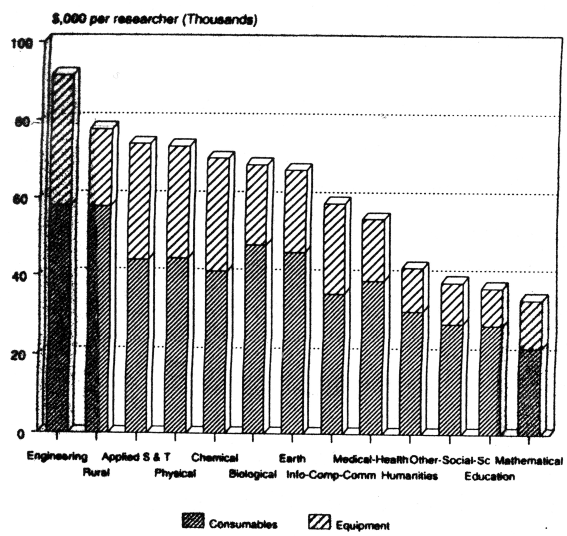


Figure 7.1: 1990 R&D expenditure on consumables and equipment for selected disciplines in the higher education sector.

Fifteen years ago, the mathematical sciences were considered to be a theoretical science with little need for equipment or consumables — other than the traditional pencil, paper and wastepaper basket. It was never so, and is certainly not so now, as is explained in Chapter 6. Computers and associated software licences are essential for teachers and students. The mathematical sciences are now a laboratory-based set of subjects, not materially different in their support needs from information science. In this respect, mathematical sciences departments

[61] ibid., figure 5.2.

are seen in Figure 7.1 to be significantly underfunded in comparison with information science departments.[62] We therefore repeat the following recommendation first made in Chapter 6:

**Recommendation 11**

- ☐ Departments and universities should ensure that staff and students have access to appropriate computers, software, support staff and network connections. To support such infrastructure for advanced teaching, research and communications, mathematical sciences departments should be funded on a comparable basis to computer science departments.

[**DEET, AVCC, Deans**]

To conclude this section, we note that it is sometimes difficult to ascertain just how far the mathematical sciences have penetrated into industry and other fields. In addition, we consider that it would be valuable to have better up-to-date information about the research projects under way in the mathematical sciences, including a register of ARC Large Grants and a register of PhD students. We therefore recommend:

**Recommendation 15**

- ☐ The Department of Industry, Science and Technology should introduce Field of Research classifications into applications for the 150% tax concession for industrial Research and Development.

[**DIST**]

**Recommendation 16**

- ☐ The Australian Mathematical Society is encouraged to collaborate with the other professional societies to maintain
  - a register of ARC Large Grants awarded for mathematical sciences research
  - a register of PhD students in the mathematical sciences with information including topic, supervisor, funding support, gender

[**Australian Mathematical Society**]

[62]Figure 7.1 also shows, astonishingly, that mathematical sciences departments are underfunded for consumables with respect to humanities departments.

## 7.3 ARC Funding; Arguments for Diversification of Funding

Funding by the Australian Research Council is considered in Chapter 2, and, in particular, in Tables 2.2a and 2.2b. In that Chapter, we reach the conclusion that mathematical sciences researchers were winning a fair share of the limited funds distributed by the ARC and that inter-disciplinary research involving the mathematical sciences similarly is effectively funded relative to other discipline areas. ARC funding is, however, difficult to obtain by isolated, small and provincial research groups. Many mathematical sciences researchers submitted, therefore, that they had no reasonable access to ARC funds.

There are a number of strong arguments why mathematical scientists should diversify their funding sources for research activities. These include:

- to develop closer links with users of research and the wider community
- to obtain fresh and vital material for courses, and to improve the quality of undergraduate and postgraduate education
- to make a more direct contribution to the wealth of the nation
- to contribute to the development of a culture of innovation in Australia
- to obtain funding that is relatively stable from year to year
- there may be no reasonable chance of immediate access to ARC Large Grants

Other funding sources than the ARC do exist, for example, the Industry Research and Development Board of the Department of Industry, Science and Technology (DIST), industry associations, collaborative grants with government agencies like CSIRO and DSTO, and direct consulting with clients. International activities are also possible, such as those outlined in Section 3.6. Funding from such sources would entail a modest shift towards the Experimental Development end of the R&D spectrum, but this should be comfortably accommodated given the present broad spread of activities in the mathematical sciences in Australia.

In Section 3.6 we comment on various technology transfer mechanisms and recommend (Recommendation 6a) that mathematical scientists should bid more vigorously for funding available through existing government programs. The present funding base for research in the mathematical sciences is relatively narrow, consisting as it does primarily of ARC Large and Small Grants and as part of a block allocation which involves service teaching commitments. The following recommendation is aimed at broadening the funding base.

**Recommendation 17**

☐ To broaden the funding base for the profession, mathematical sciences researchers are encouraged to apply for funds from a wide range of sources including

- ARC collaborative grants scheme
- APA (Industry) collaborative grants scheme
- the ARC Key Centres program
- competitive research grants from the Industry R&D Board of DIST
- the DIST Bilateral Science and Technology Program (for international collaboration)
- industry association funds
- other government programs including NHMRC funds

[**Academic researchers, Heads of Department, Deans**]

Information on the above funding opportunities is not always readily available. It would be useful if professional societies compiled a register of the information and made it available electronically through their WWW sites.

## 7.4 The Importance of Service Teaching

Service teaching is a vital activity because

- it ensures that mathematical sciences instruction is carried out by staff with appropriate skills and professional interests in the mathematical sciences — students have the privilege of being taught by leaders in the field
- it enables necessary mathematical sciences resources (hardware, software, library, educational materials) to be concentrated in one university department, not dispersed across many departments
- it facilitates collaboration and inter-disciplinary research with colleagues from other departments
- it helps to preserve the profession as a cohesive group, rather than allowing mathematical scientists to be distributed across many departments; this has beneficial effects for peer support

The above points provide strong grounds to believe that service teaching of mathematical sciences topics delivers better educational outcomes than would be the case if teaching is devolved to departments in which the students reside.

In addition, service teaching brings in valuable student numbers. This is a crucial element in research funding in mathematical sciences departments. According to the Australian Bureau of Statistics[63], some 65% of higher education R&D is funded through (the research component of) general operating grants given to higher education institutions in support of both teaching and research. For most mathematical sciences departments, service teaching forms a significant fraction of their overall teaching activity.

In receiving submissions to this Review, the Working Party formed the view that mathematical sciences researchers generally do not give enough weight to their service teaching. In some instances, loss of service teaching to client departments had already occurred, and there is pressure for more client departments to take over service teaching. The loss of service teaching would be generally detrimental to students, to the mathematical sciences profession and to client disciplines. We therefore recommend that:

**Recommendation 18**

☐ Departments must recognise the role that service teaching plays in maintaining the mathematical level of other disciplines and fostering links with those disciplines. Departments should be attentive to nurturing service teaching arrangements and meeting the needs of client disciplines. Universities should beware of fragmenting the mathematical sciences through devolution of service teaching.

[**Heads of Department, Deans, AVCC**]

[63]ibid., p.41.

# 8

# National Centres

## 8.1 Introduction

In this chapter, we consider the case for establishment in Australia of national centres for mathematical sciences research and applications. Possible activities in such centres span the full spectrum from pure basic research through to the development of links[64] between the nation's researchers and potential users of their skills in business and the community. We discuss a range of styles and activities for these centres, describe overseas examples, and suggest how appropriate centres could be established in Australia.

We start by looking at existing mechanisms by which such centres could be funded in Australia. There are three main mechanisms.

1. *Special Research Centres* (funded by the Australian Research Council). These centres have the primary objectives of supporting basic research, maintaining the research base, and encouraging the development of international links. Secondary and tertiary objectives are, respectively, training high quality graduates, and contributing to applied research and services. The only mathematical centre in Australia of this type was the Centre for Mathematical Analysis which ran from 1982 to 1990 at the Australian National University.

   In 1994, there were 18 of these centres operating in 11 universities. In total, these 18 centres received $12.7 million in ARC grants under the Special Research Centres program. Fields of research included basic science (5 centres), engineering (2 centres), mineral processing (2 centres), biological sciences (4 centres), information technology (1 centre), and social sciences (4 centres). There is no current centre in the mathematical sciences.

[64]For a thorough analysis of the development of links between universities and industry in Australia, see *Crossing innovation boundaries: the formation and maintenance of research links between industry and universities in Australia*, National Board of Employment, Education and Training, Commissioned Report 26, November 1993.

2. *Key Centres for Teaching and Research* (funded by the Australian Research Council). These centres have the primary objective of delivering applied research and services. Secondary and tertiary objectives are, respectively, training high quality graduates, and supporting basic research and maintaining the research base.

   In 1994, there were 35 of these centres operating in 19 universities. In total, these centres received $7.1 million in ARC grants under the Key Centres program. One of these centres has a specific mathematical focus (but not at the research or advanced mathematical services level envisaged in this report), namely the Key Centre for School Science and Mathematics at Curtin University of Technology. The other centres cover a broad range of disciplines. The ARC has made available $2.4 million a year for seven new Key Centres that began operating in mid 1995; none has a specific mathematical focus.

3. *Co-operative Research Centres* (funded by the Department of Prime Minister and Cabinet). By bringing researchers from universities and government laboratories together with industrial and other users of research outcomes, the CRC program contributes to the development of internationally competitive industry sectors. In terms of the Standard Research Classification, the CRC program is aimed largely at applied research, with some spillover to strategic basic research and some to experimental development.

   Up to mid 1994, 51 CRCs were in operation, with each receiving an average of about $2 million from CRC program funds. Other necessary resources are contributed by participating organisations. A further 10 CRCs were announced late in 1994.

   The CRCs span the following sectors in the Australian economy: manufacturing technology (9 centres), information and communications technology (8 centres), mining and energy (9 centres), agriculture and rural based manufacturing (15 centres), environment (12 centres), medical science and technology (8 centres).

   A few CRCs, primarily in the information and communications technology sector, are based on sub-disciplines that have wide generic applicability. In general, however, the CRC program caters only for sub-disciplines that can be aligned closely with sub-sections of the economy or environment, and usually where there are a handful of muscular supporters. Although the mathematical sciences are central to the competitiveness of modern economies, they do not fit comfortably with the existing CRC mould. Note, however, that the mathematical sciences do play an essential role in some CRCs, amongst them the CRC for

Aerospace Structures, the CRC for Southern Hemisphere Meteorology, the CRC for Robust and Adaptive Systems, and the CRC for Sensor Signal and Information Processing.

## 8.2 International Examples

Internationally, there are two models that have been effective in encouraging general activity and achievement in the mathematical sciences.

The first model is exemplified by the Institute for Advanced Study at Princeton, subsequently adopted successfully by the Institute des Hautes Etudes Scientifiques at Bures-sur-Yvette near Paris. This model consists of a nucleus of outstandingly qualified permanent academic staff, in close proximity to a large university but with independent infrastructure and administration. An institute of this type typically provides facilities for senior mathematical scientists on sabbatical leave and for selected postdoctoral and research fellows. The research program is largely dictated by the interests of the permanent staff and senior visitors. Activities revolve around seminar series and occasional workshops. The main aims are to provide a productive environment for visitors and to foster the development of postdoctoral fellows through interaction with permanent staff and senior visitors.

The second model is typified by MSRI (Mathematical Sciences Research Institute) in Berkeley, IMA (Institute for Mathematics and its Applications) in Minnesota, the Fields Institute in Canada, and the Newton Institute in Cambridge. These institutes have no permanent academic staff. They typically have a Director — an active mathematical scientist of distinction — with a five year appointment, who is supported by a permanent administrative staff. These centres are attached to a major university, but have independent infrastructure. Their activities are based on special programs which usually run from six to twelve months. The programs are selected by a scientific committee with strong representation from outside the university where the institute is located, and they are organised and coordinated by mathematical scientists on secondment to the institute for the period of the program. Program activities include workshops and conferences. Support is typically provided for short term visits by senior mathematicians and longer visits by postdoctoral fellows. In general there is no specific emphasis on graduate training, but the Fields Institute has begun a program which acts as a focal point for students from around the country. Because these institutes have no permanent staff with personal research interests, they have great flexibility and can remain at the forefront of research developments. In this way, they are able to provide ongoing national research leadership.

Although we have cited only four examples of this second type of research institute in the mathematical sciences, the model has now been adopted by some twenty centres worldwide. There was an inaugural meeting of Directors of International Mathematical Sciences Institutes in Zurich in August 1994 and a second in Hamburg in August 1995. At the first meeting, it was decided to create a communications and information network for research programs at the national and international level. At the second meeting, an Executive Committee was established to formalise the membership of IMSI, to develop mechanisms for the admission of additional members and to discuss and further explore opportunities for cooperative ventures between IMSI member institutes. Professor Derek Robinson of the Centre for Mathematics and its Applications, ANU, was elected to membership of the Executive Committee and this ensures that Australia is involved, at least initially, in the development of this organisation. It is likely that IMSI will increase in international importance and influence. It is important that Australia retain its involvement, but this is unlikely without the development of a true National Centre.

There are also national centres that undertake applied research in the mathematical sciences. Here, there is not such a range of successful examples to cite. Australia's own CSIRO Division of Mathematics and Statistics has part of this mission in that it undertakes strategic research and experimental development. Importantly, however, CSIRO DMS does not have a major focus in postgraduate education, and thus does not capture benefits accessible through an industrially-directed postgraduate program. Until its dissolution a few years ago, the Applied Mathematics Division of New Zealand's DSIR had a similar role to CSIRO DMS. The Fraunhofer Institutes in Germany have a national and regional role which is directed strongly towards experimental development in collaboration with industry, but they too miss out on benefits of postgraduate education. Perhaps the best example worldwide of a national applied research centre in the mathematical sciences is France's INRIA[65] — this does have a nationally-directed and balanced program of strategic research, technology transfer, interaction with spin-off companies, joint appointments with universities, and supervision of postgraduate students.

Many academic groups worldwide have attempted to build up an industrial focus for their work, whilst retaining as their dominant activity the education of undergraduate and postgraduate students. The number in this category worldwide must be in the hundreds; particularly strong examples known to us are university groups in Kaiserslautern (Germany) and Greenwich (England). However, none of these groups has a national focus.

[65] Institut National de Recherche en Informatique et en Automatique.

## 8.3 National Research Centre for the Mathematical Sciences

The Working Party found near universal support for the creation of a national mathematical sciences research centre with a similar structure to MSRI, IMA, the Fields Institute and the Newton Institute (see Section 8.2 for details of these centres).

The 1992 committee which reviewed ARC Research Funding for the mathematical sciences through its Large Grants Scheme made a firm recommendation to establish such a centre[66]. Their recommendation was supported by detailed submissions to that Review by the Australian Mathematical Society and the Statistical Society of Australia. It was understood that the proposed centre would cover all areas of the mathematical sciences, including computational aspects. The arguments and the recommendations of the 1992 committee remain valid.

Because of the human resource features described in Section 4.1 (skewed age distribution, gender inequity, lack of current opportunities for postdoctoral fellows and researchers seeking to start a professional career, and a likely surge of replacement staff required in ten or so years time), it would be appropriate for the proposed centre to have a stronger postdoctoral emphasis than is customary overseas. This could help to smooth out likely rapid changes in human resource needs caused by the present age structure of university mathematical sciences departments. It may also mean that the centre can serve as a resource for the Asia-Pacific region.

The first step in the creation of such a centre would be for the mathematical sciences community to agree on the structure and activities of the new centre, prior to a decision on its location. The professional societies should be fully involved in these initial discussions. Subsequently, all Australian universities could be invited to make bids to host the centre and to provide the necessary infrastructural support. The final decision on location should then be made by a broadly based panel of leading Australian mathematical scientists appointed by the professional societies. It would be appropriate for the National Committee for Mathematics to co-ordinate this process. This procedure would not only be perceived as fair by the mathematical sciences community, but would also put pressure on the bidders to maximise their commitment to the centre.

[66] *Review of Grants Outcomes No. 9: mathematical sciences 1987–91*, Australian Research Council, 1992, Recommendation 10.

We note that the National Committee for Physics has come to a similar conclusion about a national centre for theoretical physics organised along flexible lines as described above. That Committee organised competitive bids, and now proposes the creation of a centre in Adelaide supported by an Adelaide–ANU–Flinders–UNSW consortium. (This initiative arose out of the recent ARC review of physics.)

The benefits of the proposed mathematical sciences research institute should include:

- development of a national capability to undertake basic mathematical sciences research of the highest calibre
- development of the broad base of knowledge necessary for subsequent applied research and experimental development in the mathematical sciences
- support of cross-disciplinary basic research
- career development opportunities for postdoctoral fellows and researchers at the start of their careers
- the opportunity to improve the gender imbalance in the mathematical sciences through, for example, development of special programs for talented female students
- enhanced research and education links in the Asia-Pacific region
- contribution to research, worldwide, through publications and enhanced postgraduate training
- a vigorous international visitors program to keep Australia abreast of international developments
- co-ordination of activities on a national basis, thereby reducing duplication of effort and expenditure, whilst assuring that teams of suitable size would be available to address major research topics

The Working Party considers that these benefits are nationally valuable and could be obtained largely from current ARC programs, with only relatively small changes in policy. Existing special research centres are formed around outstanding researchers or groups of researchers. In contrast, we propose that the National Centre in the Mathematical Sciences should be formed around programs and sub-disciplines. Based on the size of existing Special Research Centres, it is anticipated that the proposed centre should receive funding in the range $400,000–$900,000 *per annum*.

There also remains the question of location of the National Centre. That was eventually resolved in Canada in respect of the Fields Institute by inviting universities to offer facilities. We therefore recommend:

**Recommendation 19a**

- ☐ The Australian Research Council should facilitate application under the SRC program by the mathematical sciences disciplines for a National Research Centre in the mathematical sciences.

**Recommendation 19b**

- ☐ The National Committee for Mathematics should conduct a competitive tender amongst universities prepared to offer funds to be the site of a proposed National Research Centre in the mathematical sciences in similar style to MSRI, IMA, the Fields Institute or the Newton Institute.

[**ARC, National Committee for Mathematics**]

## 8.4 CRC for Industrial Applications of the Mathematical Sciences

In addition to the basic research centre described above, we believe that there would be considerable national benefit in establishing a Centre for Industrial Applications of the Mathematical Sciences. The CRC program provides a mechanism for such a Centre to be established, and it would enable concentration of effort in areas that rely heavily on the mathematical sciences, are generically applicable to several industry sectors, and are rapidly developing. Prime examples include computational fluid dynamics, image analysis and operations research.

It is important to note that CRCs involve substantial postgraduate and postdoctoral training. At the moment, the country's mathematical talent is dispersed across many institutions and is not used optimally for training postgraduates and for technology transfer. In particular, CSIRO Division of Mathematics and Statistics does undertake such R&D in the mathematical sciences but does not have a significant educational role, whilst the universities provide the educational training but do not have good industrial connections on a national scale. The proposed CRC for Industrial Applications of the Mathematical Sciences would provide a way to link these currently disjoint activities.

We envisage a CRC based on CSIRO DMS, but with clear and effective connections with protagonists in the university sector. As with many other CRCs, the infrastructure and administration would be independent of organisations such as CSIRO and universities. The CRC would have a full time Director, being an active mathematical scientist of distinction with experience in industrially-directed activities, plus a small support staff which would include marketing expertise. In-kind contributions (that is, specialist researchers with appropriate support) would be provided by CSIRO DMS and participating universities, with perhaps 20 industrial partners providing cash support. The participating partners could come from a range of industry sectors: manufacturing, mineral processing, finance, services, ...

To set up such a CRC would require a number of issues to be successfully addressed, including the development of courses and establishment of management processes to handle contract research between partners. It would have some advantages if collaboration were to take place of the proposed CRC and the Special Research Centre described in the previous section. Co-location of these initiatives, if feasible, would facilitate the collaboration.

The principal activities envisaged for the proposed CRC include:

- collaborative research with industry partners, particularly on generically important topics (*e.g.* scheduling, simulation, new computational methods for industrial processes, image analysis)
- supervision of PhD students in industrially relevant topics
- postdoctoral research on major generic areas
- monitoring of rapidly emerging areas (*e.g.* wavelets) and development of a capability in them
- hosting the Mathematics-in-Industry Study Group
- some contract research
- liaison with small to medium enterprises (SMEs)
- continuing specialist education through courses and workshops
- coordination of specialist master's level courses in industrial mathematical sciences
- development of international links through a visitors program
- acting as a clearing house for research providers and potential research users; in particular, development of a database of interested contributors and users of the mathematical sciences

The principal benefits of such a CRC would be:

- anticipation of Australia's generic industrial needs, and development of a capability to meet them
- postgraduate students who would be highly suitable to industry's needs
- reduced duplication of skills, hardware, software and other infrastructure across a range of institutions
- value-adding to Australian enterprises through collaborative research carried out using a 'best teams' approach
- a strong and visible link in technology transfer from the mathematical sciences to users
- a flagship activity that would help to develop a culture of innovation in Australia because of the pervasive effect of the mathematical sciences

In view of these significant national advantages, we make the recommendation:

**Recommendation 20**

☐ The government should identify the mathematical sciences as an under-represented discipline in the CRC program and should therefore invite proposals to establish a CRC for Industrial Applications of the Mathematical Sciences.

**[DPMC, Chief Scientist]**

# Appendix

## Table of Contents



## Sponsors

This review was funded by a mixture of in-kind support, cash sponsorship and institutional support for members of the Working Party. Direct cash contributions prior to November 1995 are gratefully acknowledged below. The principal expenditures were: salary of the Executive Officer, salary of Secretary, and travel expenses of the Working Party. Some of the travel expenses for the Working Party were met by their own institutions.

| | |
|---|---|
| National Board of Employment, Education and Training | $50,000 |
| University departments | $21,400 |
| Professional Societies | $5,200 |
| CSIRO Leadership Development Program | $5,000 |
| NSW Office of Economic Development | $3,000 |


## Acronyms Used in this Report

| | |
|---|---|
| AAMT | Australian Association of Mathematics Teachers |
| ABS | Australian Bureau of Statistics |
| AIDS | Acquired Immune Deficiency Syndrome |
| AMS | American Mathematical Society |
| AMSC | Australian Mathematical Sciences Council |
| ANU | Australian National University |
| ANZIAM | Australian and New Zealand Industrial and Applied Mathematics |
| APA(I) | Australian Postgraduate Award (Industry) |
| ARC | Australian Research Council |
| ARGS | Australian Research Grants Scheme |
| ASOR | Australian Society for Operations Research |
| ASTA | Aerospace Technologies of Australia |

| | |
|---|---|
| ATO | Australian Taxation Office |
| AustMS | Australian Mathematical Society |
| AVCC | Australian Vice-Chancellors' Committee |
| BHP | The Broken Hill Proprietary Company Ltd |
| CAUT | Committee for the Advancement of University Teaching |
| CFD | computational fluid dynamics |
| CRA | Conzinc Riotinto Australia Pty Ltd |
| CRC | Cooperative Research Centre |
| CRC–AS | Cooperative Research Centre for Aerospace Structures |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| DEET | Department of Employment, Education and Training |
| DIST | Department of Industry, Science and Technology |
| DMS | Division of Mathematics and Statistics (CSIRO) |
| DPMC | Department of Prime Minister and Cabinet |
| DPI | Queensland Department of Primary Industries |
| DSIR | Department of Scientific and Industrial Research (NZ) |
| DSTO | Defence Science and Technology Organisation |
| EFTSU | equivalent full time student unit |
| ETSA | Electricity Trust of South Australia |
| FASTS | Federation of Australian Scientific and Technological Societies |
| FFT | fast Fourier transform |
| FOR | Field of Research |
| GDP | Gross Domestic Product |
| HECS | Higher Education Contribution Scheme |
| IAS | Institute of Advanced Studies |
| IMA | Institute for Mathematics and its Applications |
| IMSI | International Mathematical Sciences Institutes |
| MELA | Mathematics Education Lecturers Association |
| MERGA | Mathematics Education Research Group of Australasia |
| MISG | Mathematics-in-Industry Study Group |
| MS/OR | management science and operations research |
| MSRI | Mathematical Sciences Research Institute |
| NHMRC | National Health and Medical Research Council |
| NRC | National Research Council (USA) |
| NZMS | New Zealand Mathematical Society |
| OECD | Organisation for Economic Cooperation and Development |
| ODE | ordinary differential equation |
| PDE | partial differential equation |
| RAM | random access memory |
| RCI | relative citation impact |
| R&D | research and development |
| RMIT | Royal Melbourne Institute of Technology |
| SCI | Science Citation Index |
| SEO | Socio-Economic Objective |
| SIAM | Society for Industrial and Applied Mathematics (USA) |
| SME | small to medium enterprise |
| SRI | Summer Research Institute |
| SSA | Statistical Society of Australia |
| TIMSS | Third International Mathematics and Science Study |
| TRIP | Teacher Release to Industry Program |
| UNSW | University of New South Wales |
| WWW | World Wide Web |

## Discussion of the Questionnaires

The Working Party had two main mechanisms for receiving input to this review: distribution of questionnaires, and half day meetings in many large cities.

Five separate questionnaires were developed: for university mathematical sciences departments, for professional societies, for Australian enterprises that use advanced mathematical services, for CSIRO divisions and CRCs, and for industry organisations. The questionnaires contained questions that elicited specific facts (*e.g.* age and gender profile of staff, source of funds, number of PhD students) as well as open-ended questions. We also requested names of appropriate people for follow up interviews — many people so nominated were invited to attend subsequent half day meetings.

Over 600 questionnaires were distributed. The mailing list included every mathematical sciences department in the country, every CSIRO division, every CRC, state and federal government departments, and about 400 private companies (names compiled by lists generously provided by state departments of economic development and the like).

We had nearly a 100% response rate from mathematical sciences departments, less than a 10% response rate from private companies, and something in between these limits for CSIRO divisions and CRCs. Many of the university responses were very carefully prepared. They also provided the impetus for individual members of staff to make personal submissions (see list later).

Two supplementary mailouts were arranged to obtain further details that had been omitted when the basic questionnaires were designed. These supplementary details related to the importance of international visitors, to the gender balance of PhD students, and to the number of postdoctoral fellows in the mathematical sciences in Australia.

## List of Mathematical Sciences Departments

†denotes submission of questionnaire to the review.

†Australian National University, Centre for Mathematics and its Applications, Department of Applied Mathematics, Department of Statistics

Ballarat University College, School of Mathematics and Computing

†Central Queensland University, Department of Mathematics and Computing

†Charles Sturt University, Mitchell, Department of Mathematics

†Charles Sturt University, Riverina, Department of Mathematics

†Curtin University of Technology, School of Mathematics and Statistics

†Deakin University, School of Computing and Mathematics, Geelong Campus, Rusden Campus and Warrnambool Campus

†Edith Cowan University, Department of Mathematics

†Flinders University of South Australia, Discipline of Mathematics; Discipline of Statistical Science

†Griffith University, School of Applied Mathematics and Statistics

†James Cook University of North Queensland, Department of Mathematics and Statistics

†La Trobe University, School of Mathematics, School of Statistics

Bendigo School of Business, Department of Mathematics

†Macquarie University, Mathematics Department, Statistics Discipline, Actuarial Studies

†Murdoch University, School of Mathematical and Physical Sciences

†Monash University, Department of Mathematics

Northern Territory University, School of Mathematics

†Queensland University of Technology, School of Mathematics

†Royal Melbourne Institute of Technology, Department of Mathematics, Engineering Mathematics, Operations Research, Statistics

†Swinburne University of Technology, Department of Mathematics

†University of Adelaide, Department of Pure Mathematics, Department of Applied Mathematics, Department of Statistics

†University of Canberra, Mathematics Group, Statistics Group

†University of Melbourne, Department of Mathematics, Department of Statistics, Centre for Actuarial Studies

†University of Newcastle, Department of Mathematics, Department of Statistics

†University of New England, Applied Mathematics, Pure Mathematics, Statistics

†University of New South Wales, Australian Defence Force Academy, Department of Mathematics

†University of New South Wales, School of Mathematics

†University of Queensland, Department of Mathematics

†University of South Australia, School of Mathematics

†University of Sydney, School of Mathematics and Statistics

†University of Southern Queensland, Department of Mathematics and Computing

†University of Tasmania, Department of Mathematics

†University of Technology Sydney, Mathematics Unit, Computational Mathematics Unit, Statistics and Operations Research Unit

†University of Western Australia, Department of Mathematics

†University of Wollongong, Department of Applied Statistics, Department of Mathematics

†University of Western Sydney, Department of Mathematical Sciences

†Victoria University of Technology, Department of Computer and Mathematical Sciences

## List of Meetings Held

The Working Party held a number of half day meetings in late 1994 in various cities so as to receive direct input into the review. These meetings fell into two categories: university meetings and industry meetings. The hospitality of the hosts is gratefully acknowledged.

| | | |
|---|---|---|
| Victoria<br>4 October | Mathematics Department<br>Monash University | BHP Research Laboratories |
| Victoria<br>5 October | Department of Mathematics<br>RMIT | Investment Centre Victoria<br>Melbourne |
| Queensland<br>25 October | Department of Mathematics<br>James Cook University | Department of Mathematics<br>James Cook University |
| Queensland<br>26 October | Department of Mathematics<br>University of Central Qld | Department of Mathematics<br>University of Central Qld |
| Queensland<br>27 October | Qld Institute of Technology | Qld Institute of Technology |
| ACT<br>9 November | Australian National University | Chief Minister's Dept |
| New South Wales<br>23 November | University of New South Wales | Bain & Co |
| New South Wales<br>24 November | Department of Mathematics<br>Macquarie University | CSIRO DMS |
| South Australia<br>6 December&<br>7 December | University of Adelaide | Dept of Primary Industries |
| Western Australia<br>8 December | University of Western Australia | Dept of Commerce and Trade |

## List of Participants at Industry Meetings

*Industry Meeting – BHP Research Laboratories*
*Tuesday 4 October, 2.00 – 5.00 pm*

Mr P Ellis, BHP
Dr M Harding, The Preston Group
Dr M Krishnamoorthy, CSIRO Division of Mathematics & Statistics
Dr J McCarthy, BHP
Dr J Perry, CSIRO Division of Mineral and Process Engineering
Dr B Sawford, CSIRO Division of Atmospheric Research
Dr A N Stokes, CSIRO Division of Mathematics & Statistics
Dr A Uhlherr, CSIRO Division of Chemicals & Polymers
Mr J Youngman, RACV

*Industry Meeting – Investment Centre Victoria*
*Wednesday 5 October, 9.15 am – 12.45 pm*

Dr J Hopper, Public Health & Community Medicine
Dr L Irlicht, CRC Cochlear
Mr P Kennedy, Moldflow Pty Ltd
Mr D Lock, Hawker de Havilland
Mr D Potter, National Bank
Dr D Rees, CRC – Aerospace Structures
Mr J Salamito, Norwich Union
Dr D Scott, ASTA
Mr B Taylor, Dataplex Pty Ltd

*Industry Meeting – James Cook University*
*Tuesday 25 October, 3.00 – 5.00 pm*

Mr C Dyck, Copper Refineries Pty Ltd
Mr M Elliot, Burdekin Resources
Mr S Hillman, Great Barrier Reef Marine Park Authority
Mr S Vigh, CSR Sugar Mills Group
Mr C Steinberg, Australian Institute of Marine Science

*Industry Meeting – Central Queensland University*
*Wednesday 26 October, 3.00 – 5.00 pm*

Ms J Arens, Comalco
Mr I Grant, Comalco
Ms L Hinton, Faculty of Health Science
Mr A Lisle, Queensland Department of Primary Industries
Mr K Tickle
Mr R Warrenor

*Industry Meeting – Queensland University of Technology*
*Thursday 27 October, 2.00 pm – 5.00 pm*

Dr J A Belward, Department of Mathematics, University of Queensland
Mr S Gay, JKMRC, University of Queensland
Mr J Holt, Opcom
Mr P Hutton, SEQEB
Mr R Pyzik, SEQEB
Dr R Schoorl, Department of Primary Industries
Mr A Swain, Department of Primary Industries
Dr I Turner, School of Mathematics, Queensland University of Technology
Dr W Whiten, JKMRC, University of Queensland

*Industry Meeting – ACT Chief Minister's Department*
*Wednesday 9 November, 2.00 – 5.00 pm*

Dr M Adena, Intstat
Dr I Doherty, DSTO
Mr E James, ASTEC Secretariat
Mr A Jorge, DIST Science & Technology Policy
Dr J Knight, CSIRO Centre for Environmental Mechanics
Ms S Linacre, Australian Bureau of Statistics
Mr I Pfennigwerth, Dexter Associates
Dr C Tarlowski, Australian Geological Survey

*Industry Meeting – Bain & Company*
*Wednesday 23 November, 3.30 – 5.30 pm*

Mr P Bell, Bain & Company
Professor R Bewley, University of New South Wales
Dr A Brace, Citibank
Dr A Bustany, Price Waterhouse Urwick
Mr W Choo, NRMA
Mr J Clark, CSIRO Division of Mathematics & Statistics
Professor P Easton, Macquarie University
Mr A Eckstein, CBA Financial Services
Mr D Economou, Armstrong Jones
Mr G Edser, SPSS Corporate Services
Dr L Gordon, William M Mercer
Mr B Nguyen, Mercantile Mutual
Mr W Phoa, Bain & Company
Mr S Sathiakumar, State Super
Mr G Wallace, BZW

*Industry Meeting – CSIRO Division of Mathematics & Statistics*
*Thursday 24 November, 9.15 am – 12.30 pm*

Dr M A Cameron, CSIRO Division of Mathematics & Statistics
Dr I Franklin, CSIRO Division of Animal Production
Dr A Green, CRC Australian Mineral Exploration Technologies
Mr J Horton, Operations Research Group
Mr P M Jellett, Charles Sturt University–Riverina
Dr A Sharpe, CSIRO Food Science & Technology

*Industry Meeting – SA Department of Primary Industries, Grenfell Centre*
*Wednesday 7 December, 9.30 am – 12.30 pm*

Mr R Blunden, F H Faulding & Co Ltd
Professor A L Carey, Department of Pure Mathematics, University of Adelaide
Professor J A Filar, School of Mathematics, University of South Australia

Dr P M Gill, Department of Applied Mathematics, University of Adelaide
Dr R Ignetik, DSTO High Frequency Radar Division
Professor R G Jarrett, Department of Statistics, University of Adelaide
Ms M Khan, F H Faulding & Co Ltd
Ms A Morella, F H Faulding & Co Ltd
Dr N Nagayama, Industrial Technology Centre of Okayama Prefecture
Dr G N Newsam, DSTO Information Technology Division
Associate Professor B J Noye, Department of Applied Mathematics, University of Adelaide
Dr M Pszczel, DSTO Guided Weapons Division
Professor E O Tuck, Department of Applied Mathematics, University of Adelaide
Dr G Walker, CSIRO Division of Water Resources

*Industry Meeting – WA Department of Commerce & Trade*
*Thursday 8 December, 2.00 – 5.00 pm*

Dr J Barker, Department of Commerce & Trade
Mr M Bertoli, World Geoscience Corporation
Dr H Mühlhaus, CSIRO Division of Exploration and Mining
Dr G Peterson, Alcoa of Australia
Dr L Townley, CSIRO Division of Water Resources

## List of Personal Submissions

A J Bishop, Monash University
P Broadbridge & R Nillsen, University of Wollongong
A L Carey & M K Murray, University of Adelaide
D Chen, University of Melbourne
E N Dancer, University of Sydney
R H Grimshaw, Monash University
J Henstridge, Data Analysis Australia Pty Ltd
A N Pettitt, QUT
J G Sekhon, University of Technology Sydney
Dr Robert G Staudte, La Trobe University

## List of Completed Questionnaires (Non-University)

*Victoria*

Albright & Wilson (Australia) Ltd
Amskan Ltd
Applied Biotechnologies Pty Ltd
ANZ Banking Group
BHP Clay Brick & Paver Institute
Clinical & Scientific Affairs, Pharmaction Pty Ltd

Comalco Research Centre
CRC for Aerospace Structures Ltd
CRC for Intelligent Manufacturing Systems & Technologies
CRC New Technologies for Power Generation
CRC for Southern Hemisphere Meteorology
CSIRO Division of Atmospheric Research
CSIRO Division of Materials Science & Technology
CSIRO Division of Mathematics & Statistics
CSIRO Division of Mineral & Process Engineering
CSR Humes Pty Ltd
Dataplex Pty Ltd
Ford Motor Company of Australia Ltd
Hawker de Havilland Victoria
Holden's Engine Company
Moldflow Pty Ltd
National Australia Bank
National Forge Ltd
Peter MacCallum Cancer Institute
RACV Ltd
Telecom Australia Research Laboratories
The Preston Group Pty Ltd
Uncle Tobys Company

*Queensland*

Australian Institute of Marine Science
BHP Australia Coal Pty Ltd
Copper Refineries Pty Ltd
CRC for Distributed Systems Technology
CRC for Mining Technology & Equipment
CRC for Tropical Plant Pathology
CSIRO Division of Tropical Animal Production
CSR Sugar Mills Group
Great Barrier Reef Marine Park Authority
James Cook University of North Queensland, Physics Department
Julius Kruttschnitt Mineral Research Centre
National Centre for Multidisciplinary Studies of Back Pain, James
Cook University of North Queensland
Opcom Pty Ltd
Queensland Department of Primary Industries
South East Queensland Electricity Corporation
The Atherton Tableland Co-operative Dairy Association Ltd

*ACT*

AOFR Pty Ltd
Australian Bureau of Agricultural & Resource Economics
Australian Bureau of Statistics
CEA Technologies Pty Ltd
Cryptomathematics Research Group, DSTO, Department of Defence
CSIRO Centre for Environmental Mechanics
CSIRO Division of Entomology
Dexter Associates
Intstat Australia Pty Ltd

*NSW*

AMP Investments Australia Ltd
AWA Ltd
Bain & Company
Barra International
CBA Financial Services
Citibank
CRC for Australian Mineral Exploration Technologies
CRC for Eye Research & Technology
CSIRO Division of Animal Production
CSIRO Division of Applied Physics
CSIRO Division of Coal & Energy Technology
CSIRO Division of Food Science & Technology
CSIRO Division of Mathematics & Statistics
CSIRO, IAPP Biometrics Unit
Goodman Fielder Ingredients Ltd
Lend Lease Corporate Services Ltd
NSW Agriculture
Operations Research Group
Pirelli Cables Australia Ltd
SPSS Corporate Services

*South Australia*

Applied Design Development Pty Ltd
CRC for Soil and Land Management
CSIRO Division of Water Resources
DSTO, Airframes & Engines Division
DSTO, Electronic Warfare Division
DSTO, Guided Weapons Division
DSTO, High Frequency Radar Division
DSTO, Information Technology Division
F H Faulding & Co Ltd
Sola International Holdings Ltd
University of Adelaide, Teletraffic Research Centre
Vision Abell Pty Ltd

*Western Australia*

Alcoa of Australia Ltd – WA Operations
Apache Energy Ltd
BP Oil Kwinana Refinery
Chemical Engineering
CRA Advanced Technical Development
CRC Australian Geodynamics
CSIRO Division of Water Resources
Data Analysis Australia Pty Ltd
Halpern Glick Maunsell Pty Ltd

### *Professional Associations*

Mathematics Education Research Group of Australia
The Australian Mathematical Society
Australian and New Zealand Industrial and Applied Mathematics
Statistical Society of Australia Inc
Combinatorial Mathematics Society of Australasia
Australian Society for Operations Research

### *Industry Sector Associations*

Australian Mineral Industries Research Association
Environment Management Industry Association of Australia

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