2016 National Research Infrastructure Roadmap Capabilities Issues Paper - Response

Submission Template

2016 National Research Infrastructure Roadmap Capability Issues Paper

Submission No: ***(to be completed by Departmental staff)***	
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Would you like your submission to remain confidential, i.e. not published on the website?	**NO**

Question 1: Are there other capability areas that should be considered?

There is a wide and deep mathematical sciences capability gap. It is the “at scale”, flexible engagement of mathematical sciences researchers with our innovation system in the age of data and computation. Reliance on the mathematical and statistical capacity of end users in the Science and Research Priority areas, government agencies and in Australian businesses is inadequate to the task of dealing with the major mathematical challenges of disruptive technologies and those that come with new and emerging areas of science.

AMSI believes that mathematical sciences capability needs the support of NCRIS infrastructure. In particular, we contend that this direct engagement with the mathematical sciences needs to be an explicit capability in NCRIS. We will elaborate on this point throughout our response. Appendix A contains AMSI’s argued case *“The capability gap and how to address it: NCRIS Mathematical Sciences Centre”* along with examples of major scientific breakthroughs delivered by mathematical collaborations and international examples of the sorts of infrastructure we have in mind.

The discipline’s 2016 Decadal Plan, “The Mathematical Sciences in Australian: Vision for 2025”, identified the need to (urgently) establish a national research centre to facilitate connections between researchers at both a domestic and international level and between researchers and industry. The discipline has actively worked toward filling this gap through AMSI’s research and research training programs along with ACEMS, CEED and MASCOS Centres of Excellence, the Mathematics and Statistics Industry Study Group and the ATN’s Industrial Doctoral Training Centre. However, the pervasiveness and critical importance of mathematical sciences to Australia’s future requires national recognition of this fundamental research capability and its support through NCRIS.

AMSI endorses the new MATRIX initiative led by Monash and Melbourne as a promising and important step in establishing vital new infrastructure in the form of a venue for residential research programs that exists in most OECD countries. Supported through NCRIS it will become a long lasting national asset of benefit to the discipline, significantly enhancing Australia's capability for international and industry collaboration in the mathematical sciences.

Question 2: Are these governance characteristics appropriate and are there other factors that should be considered for optimal governance for national research infrastructure.

We agree that these characteristics are appropriate and the mathematical sciences are in a good position to deliver an effective governance structure for research infrastructure through AMSI, its national peak body.

Question 3: Should national research infrastructure investment assist with access to international facilities?

Yes, investment should assist with access especially through the engagement with Australian infrastructure facilities. In other words, by supporting direct facility to facility engagement. For example, shared programs and exchange of expert personnel would bring considerable benefit to mathematical sciences infrastructure and hence to research. Rapid adoption of research outcomes will also be facilitated.

Question 4: What are the conditions or scenarios where access to international facilities should be prioritised over developing national facilities?

For the mathematical sciences access to international facilities should not be prioritised over national facilities because this undermines the critical need to raise domestic collaborations and capability.

Question 5: Should research workforce skills be considered a research infrastructure issue?

Yes. The need for mathematical and statistical sophistication and an ability to deal with models and interpret data and other outputs is becoming a key skill for researchers in a range of fields. This needs to be linked to “mathematics” in the capacity area “Advanced Physics, Chemistry, Mathematics and Materials” in the same manner as which “data” – interpreted from a user prospective – in other capacity areas is linked to “data” in the capacity area “Data for Research and Discoverability”. Also see our response to Question 6.

Question 6: How can national research infrastructure assist in training and skills development?

PhD training should continue to take place under the auspices of the universities but there is significant benefit to be had in PhD students undertaking (optional) .internships at research infrastructure facilities. Similarly, industry doctoral training students can naturally be employed as research support staff. We mention both AMSI Intern and the ATN's Industrial Doctoral training Centre in this regard.

Question 7: What responsibility should research institutions have in supporting the development of infrastructure ready researchers and technical specialists?

See the response to Question 6 above.

Question 8: What principles should be applied for access to national research infrastructure, and are there situations when these should not apply?

AMSI endorses the current arrangements as they apply at NCI for example.

Question 9: What should the criteria and funding arrangements for defunding or decommissioning look like?

AMSI agrees with the general position in the Issues paper but has no comments on the specifics.

Question 10: What financing models should the Government consider to support investment in national research infrastructure?

The mathematical sciences infrastructure we are envisaging would raise some funds from industry collaboration. Potential host universities would make a cost contributions and AMSI would contribute. From these sources we would expect to co-fund up to 50%.

Question 11: When should capabilities be expected to address standard and accreditation requirements?

We would expect mathematical sciences products to meet international standards for mathematical and statistical software. Naturally ethics standards would also be met by all supported research collaborations.

Question 12: Are there international or global models that represent best practice for national research infrastructure that could be considered?

There are many diverse examples of best practice in mathematical sciences research engagement to be found around the world. We have identified many in the argued case *"The capability gap and how to address it: NCRIS Mathematical Sciences Centre"* in Appendix A.

Best practice in the provision of research institute infrastructure includes the Banff International Research Station, Mathematisches Forschungsinstitut Oberwolfach and the Newton Institute. We refer the reader to Appendix B of the 2016 Decadal Plan, "The Mathematical Sciences in Australian: Vision for 2025".

Question 13: In considering whole of life investment including decommissioning or defunding for national research infrastructure are there examples domestic or international that should be examined?

No comment.

Question 14: Are there alternative financing options, including international models that the Government could consider to support investment in national research infrastructure?

See our response to Question 10.

Health and Medical Sciences

Question 15: Are the identified emerging directions and research infrastructure capabilities for Health and Medical Sciences right? Are there any missing or additional needed?

Question 16: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 17: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Health and Medical Sciences capability area?

The mathematical and statistical needs of the Health and Medical Sciences must be explicitly assessed, especially in ensuring the agile response of this area to disruptive medical technologies. Active, structural collaborations with statisticians and mathematicians are a sound means of mitigating future shock in this respect.

Environment and Natural Resource Management

Question 18: Are the identified emerging directions and research infrastructure capabilities for Environment and Natural Resource Management right? Are there any missing or additional needed?

Question 19: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 20: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Environment and Natural Resource Management capability area?

The mathematical and statistical needs of the Environment and Natural Resource Management are significant from biosecurity to tsunami modelling. It is our strong view that new infrastructure to support mathematical collaborations with end users in these domains will have immediate and long lasting benefit.

Advanced Physics, Chemistry, Mathematics and Materials

Question 21: Are the identified emerging directions and research infrastructure capabilities for Advanced Physics, Chemistry, Mathematics and Materials right? Are there any missing or additional needed?

Yes, the omission of mathematics in this section and in the whole issues paper is stark. It is our strong view that the mathematical sciences are a fundamental capability both in their own right and as part of the Underpinning Research Infrastructure. The NCRIS Roadmap must ensure the provision of mathematical sciences capability across the entire NCRIS enterprise if for no other reason than to mitigate the risk of failure in areas such as national security and public health.

The text on p.12 of the Issues paper reads:

"In framing the capability focus areas a number of common themes have emerged. As a result some themes will appear under more than one capability focus area. This reflects the pervasive nature of national research infrastructure capability across the research landscape.

As you might expect, data is everywhere and dealt with from both a user perspective within the capability areas and as an enabling national infrastructure itself in Chapter 11 – Data for Research and Discoverability."

Mathematical and statistical modelling and analysis could and should be considered in the same light.

Indeed there should be many more ticks in the row *"Advanced Physics, Chemistry, Mathematics and Materials"* of the table on page 56 of the Issues paper. The study *"The importance of advanced physical and mathematical sciences to the Australian economy"* commissioned by the AAS and OCS paints a very different picture of the importance and pervasiveness of the mathematical sciences. An excerpt has been included in the appendices.

AMSI urges the appointment of a mathematical scientist to the capability expert group for Advanced Physics, Chemistry, Mathematics and Materials.

Under this specific capability heading we endorse the Decadal Plan's call for a national research centre in the mathematical sciences (in this context "centre" does not mean a single physical facility but rather a distributed one). There are two clear prospective NCRIS components to this, one being the need for an Australian research station with an international outlook. In this respect AMSI endorses the MATRIX initiative established by Monash and Melbourne universities which is described in Appendix G. AMSI is actively engaging with MATRIX in the delivery of its programs and it has clearly achieved proof of concept.

The second NCRIS component of this national research centre is the infrastructure facility to support mathematical engagement which proposed by AMSI in Question 1 and described in *"The capability gap and how to address it: NCRIS Mathematical Sciences Centre"* in the appendix. This facility will be a key driver of new mathematics and of the industry-research outcomes looked for in NISA.

Question 22: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

The mathematical sciences are intrinsically international and most university mathematicians have international collaborators. As a result there are many multinational programs occurring at any one time. However, the absence of significant infrastructure means that we have not been able to lead or even participate in international engagement as effectively as many of our neighbours. In particular, institute to institute engagement is limited.

Question 23: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Advanced Physics, Chemistry, Mathematics and Materials capability area?

See the response at Question 21.

Understanding Cultures and Communities

Question 24: Are the identified emerging directions and research infrastructure capabilities for Understanding Cultures and Communities right? Are there any missing or additional needed?

Question 25: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 26: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Understanding Cultures and Communities capability area?

While there is clearly embedded quantitative capacity in this domain the data and eResearch demands of this capability will be significantly enhanced by collaborations with statisticians and optimisers supported by the infrastructure we are proposing.

National Security

Question 27: Are the identified emerging directions and research infrastructure capabilities for National Security right? Are there any missing or additional needed?

Question 28: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 29: Is there anything else that needs to be included or considered in the 2016 Roadmap for the National Security capability area?

Australia's National Security capability is heavily dependent on the mathematical sciences and the installation of infrastructure designed to support collaborations with mathematicians and statisticians is of strategic importance.

Underpinning Research Infrastructure

Question 30: Are the identified emerging directions and research infrastructure capabilities for Underpinning Research Infrastructure right? Are there any missing or additional needed?

What is missing is a platform to support the mathematical sciences collaborations so important across almost all of the research enterprise. This is a blind spot in the issues paper. Statistics, simulation and computation are pervasive in the Roadmap but the capability to keep them current and effective is missing. For this reason we propose adding this capability to the Underpinning Research Infrastructure.

The government has made industry-research collaboration a cornerstone of NISA. What we propose is an innovative infrastructure platform which will bring these collaborations to scale in a responsive and flexible way. It will provide a mechanism for rapid adoption of mathematical innovation developing here and internationally. Without it we will continue with patchy uptake of offshore developments and not at the leading edge needed for our own national priorities.

We develop this proposal in the argued case *"The capability gap and how to address it: NCRIS Mathematical Sciences Centre"* in Appendix A.

Question 31: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 32: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Underpinning Research Infrastructure capability area?

See our response to Question 30.

Data for Research and Discoverability

Question 33 Are the identified emerging directions and research infrastructure capabilities for Data for Research and Discoverability right? Are there any missing or additional needed?

Question 34: Are there any international research infrastructure collaborations or emerging projects that Australia should engage in over the next ten years and beyond?

Question 35: Is there anything else that needs to be included or considered in the 2016 Roadmap for the Data for Research and Discoverability capability area?

Statistical and optimisation capabilities are central to Australia's strategic data resources. It is surprising that this centrality is not more clearly identified in the Roadmap. Data acquisition, storage, management and analysis requires a collaboration of disciplines so that the very latest tools are available on every side. As we have pointed out elsewhere siloing is the enemy of progress and active engagement with the mathematical sciences must be a structural part of the infrastructure provision in this area. For this reason we urge the inclusion of infrastructure supporting mathematical sciences engagement as Underpinning Research Infrastructure.

Other comments

If you believe that there are issues not addressed in this Issues Paper or the associated questions, please provide your comments under this heading noting the overall 20 page limit of submissions.

See our appendices

2016 National Research Infrastructure Roadmap **APPENDIX A**
Capability Issues Paper
AMSI Submission

The capability gap and how to address it: NCRIS Mathematical Sciences Centre

The capability gap

Mathematicians are problem solvers. And the best solutions are the ones that create new and portable mathematics. This creativity is what distinguishes the mathematical scientist from the mathematically literate engineer or scientist. Breakthrough innovations flow from this new mathematics: tomography and bioinformatics are striking examples of successful collaborations. Our innovation system ignores this collaborative capability at its peril.

Australia's big capability gap is the "at scale" flexible engagement of mathematical sciences researchers with our innovation system in the age of data and computation. Reliance on the mathematical and statistical capacity of end users in the Science and Research Priority areas and in Australian businesses is inadequate to the task of dealing with the major mathematical challenges of disruptive technologies.

The government has made industry-research collaboration a cornerstone of NISA. Collaborations in data analysis, simulation and computation are integral to the effectiveness of NCRIS. What we propose is an innovative infrastructure platform which will bring these collaborations to scale in a responsive and flexible way. It will provide a mechanism for rapid adoption of mathematical innovation developing here and internationally. Without it we will continue with patchy uptake of offshore developments and not at the leading edge needed for our own national priorities.

Some Australian mathematical scientists do of course engage with end users by various means: for example, the ARC ACEMS, CEED and earlier MASCOS and CMA Centres of Excellence, the Mathematics and Statistics Industry Study Group, past CSIRO mathematical sciences divisions, ARC Linkage projects and the AMSI Intern PhD program. However, these programs fall far short of servicing demand and they can only mobilise a part of the mathematical research community and an even smaller part of the end user world. Engagement on the scale envisaged in NISA will need an additional, new platform. Australia is a long way behind northern hemisphere nations in this respect. Bioinformatics in Australia is a notable exception and a great example of what can be achieved.

The discipline's 2016 Decadal Plan, "The Mathematical Sciences in Australian: Vision for 2025", identified the need to (urgently) establish a national research centre to facilitate connections between researchers at both a domestic and international level and between researchers and industry. The discipline has actively worked toward filling this gap through the new national MATRIX research facility provided by Monash and Melbourne and AMSI's research and research training programs along with ACEMS and MASCOS Centres of Excellence and the Mathematics and Statistics Industry Study Group. However, the pervasiveness and critical importance of mathematical sciences to Australia's future requires national recognition of this fundamental research capability and its support through NCRIS.

The concept: the capability can be elaborated by considering how to service it.

A flexible and responsive resource centre staffed by expert support personnel servicing a diverse range of mathematical engagement with sophisticated end users from universities, agencies and the private sector.

The Centre will also broker new collaborations and assist them to set up their legal and financial frameworks.

The staff will be mathematicians, statisticians, optimisers, computational scientists and interns along with administrative and business personnel. The expert staff will be sourced from both the public and private sectors.

The staff will be mobile and deliver both on site and remote services to collaborations. Secondary nodes may develop.

The Centre will be co-located with a major university mathematical sciences school with a full spectrum of research interests.

Projects will be of varying size but the imperative is to deliver proof of concept on time scales not otherwise achievable by the collaboration partners.

The Centre will be linked to centres overseas and create a channel for the rapid adoption of international innovation.

It will use other NCRIS facilities as required.

The Centre will be part of AMSI and consequently hard-wired to the discipline and its networks.

What it isn't

It is not a commercialisation facility. It will not compete with CSIRO's Data 61, Biarri or any of the universities whose business it is to commercialise research outcomes. It will however provide an articulation to commercialisation services when that's appropriate.

It is not a consultancy. It will service and broker research collaborations but it will not supply solutions direct to corporate or agency clients. It may refer such work to commercial providers. It has a broader range of capabilities than a specialist consultancy and the staff will work under the scientific direction of the collaborators.

It is not a virtual facility nor a residential facility.

It is not a Centre of Excellence (CoE). Nor is it intended to compete with or usurp the roles of CoEs. It will give mathematical scientists across the entire research system the opportunity to have their collaborations supported. It will make referrals to mathematical sciences CoEs and other expert groupings.

Who will use it

Non-mathematical clients (geoscientists, fintech specialists, machine learners, digital security people, defence optimisers, climate modellers and architects, etc.) will use it as a matching service for mathematical collaborators, theoretical and applied, and then use the resources to tie the knot. New and existing cross and multidisciplinary partnerships involving mathematical scientists will seek its resources to realise research outcomes efficiently.

Government agencies, large corporates, SMEs, start-ups, government departments will all use it.

What it will achieve

It will increase the responsiveness of the mathematical sciences to the needs of an innovation system increasingly dependent on mathematical resources.

It will radically increase the scale of research-industry and research-agency collaborations.

It will create a resource environment where research collaborations can take place efficiently.

It will bring mathematical quality and integrity to bear on the mathematical and statistical dimension of the work of agencies and companies.

It will enhance the interactions between the mathematical sciences and other domains so important for the vibrancy of our discipline and our partner domains.

It will bring specialists from the world's best practice sites to Australia.

National and international examples:

http://www.maths-in-industry.org/

MISG Australia http://mathsinindustry.com/

http://www.bath.ac.uk/imi

http://www.dwz-kairo.de/sites/default/files/Research%20in%20Germany_Mathematics.pdf

http://www.matheon.de/

http://www.limebv.nl/

http://www.scai.fraunhofer.de/en.html

Current NCRIS examples

http://www.bioplatforms.com/what-we-do/

http://www.bioplatforms.com/bioinformatics-capabilities/

http://nci.org.au/about-nci/our-role/

Detailed justification

The proposed centre will provide a structural means to connect mathematical scientists with end users of mathematical and statistical methods to solve leading edge research problems on acceptable time scales.

This national resource will add significant value and incentives to cross-sectoral and multi-disciplinary research. It will engage mathematical scientists in collaborations and provide a training facility for computational scientists, data scientists and research managers.

Unfilled demand in both directions:

Government agencies, companies, CRCs and CoEs do not generally have in-house mathematical sciences capacity or access to it and university mathematicians and statisticians do not have access to support at the scale needed to embark on industry research collaborations (much more than is available through Discovery or Linkage project grants) on acceptable time scales. This is limiting the role of the mathematical sciences in the Australian innovation system and a time when other countries have solved this problem.

Lack of technical mathematical, statistical, computational and visualisation support hampers this collaboration between mathematical scientists and high level end users. The CoE/ ITRP system support is restricted to CIs & PIs and does not encourage or facilitate opportunistic, needs-based or private sector research collaborations on a variety of scales with statisticians and mathematicians. Individual university collaborations with private industry don't always have strategic goals based around national priorities. The lack of this infrastructure considerably hampers Australia's ability to respond to international trends in such collaborative research.

Universities react institutionally to new opportunities that emerge during economic transformation on longer time scales compared to those required by emerging industries looking for mathematical infrastructure to support their development needs. Many examples exist of companies emerging from "pure research" in the mathematical sciences, Google being a standout example (it can be argued that the Google search engine success in due precisely to the input of mathematicians). Most of these have emerged in the US where there is venture capital culture that facilitates risk taking that is not replicated in Australia.

Thus we need an infrastructure that allows the sandboxing of new ideas and the nurturing of promising industries to a stage where they can establish themselves in Australia rather than exit overseas to access venture capital. Much of this analysis applies to all innovative sciences but it is clear that the digital age is not dealing an even hand to all sciences. Mathematical sciences are relative low cost and agile in their impact on the development of new industrial infrastructure. Thus a nationwide mathematical sciences facility underpinning the development needs of industry would see wide transformative impact at relatively low cost.

This model avoids the inevitable siloing of conventional university-industry partnerships.

Finally, there is an analogy with infrastructure in astronomy. Telescopy is a means of providing theoretical astronomers with a continuous source of research challenges. Through the support of external engagement this centre will provide us, across the mathematical spectrum, with a strong source of research challenges. While the challenges themselves cannot be planned in advance, the strategic means to deliver them can.

Personnel

Centre director;

Research support staff: mathematical scientists; computational scientists and IT support; some of the scientists will be seconded from universities & agencies. Interns (research support).

Administrative staff including business, marketing & comms specialists.

International specialists on short term contracts (1-6 months).

Research projects supported

Government agencies; private companies and consortia. Centres of Excellence (ARC and other); Linkage Projects; CRCs; Project durations from months to years.

Operating model

Primary location with nodes to include existing and emerging capacities, see for example, http://www.bioplatforms.com/bioinformatics-capabilities/

Some projects will be funded or subsidised based on a merit-based competition. Some will be funded on a fee for service basis. See http://nci.org.au/about-nci/our-role/

In house mathematical, computational and software expertise, supported by business staff, will provide the capacity required to support research collaborations to deliver on acceptable time scales.

Dedicated MISG-type events will scope new industry projects with researchers; business team will plan and cost projects and assist with contractual arrangements; centre staff will support timely delivery of outcomes by research and industry partners.

Hosting/resourcing Linkage projects on a pay for access basis (Linkage budgets).

Hosting/resourcing Agency/University collaborations on a pay for access basis (Agency budgets).

Resourcing CoE/CRC collaborations with mathematical scientists (CoE budgets)

Use of interns will drive scale capacity and provide a pathway for PhDs into the technical workforce. (Interns will work on the research support side, not the research side.)

Interns and technical support staff will be mobile and able to work on-site with researchers and industry partners for extended periods.

Saving lives: the mathematics of tomography | plus.maths.org

URL: https://plus.maths.org/content/saving-lives-mathematics-tomography

Saving lives: the mathematics of tomography

By Chris Budd and Cathryn Mitchell

Submitted by plusadmin on June 1, 2008

Back to the Next microscope package
Back to the Do you know what's good for you package
Back to the Constructing our lives package

Can Maths really save your life? Of course it can!! Maths has applications to many problems that are vital to human health and happiness. In this article we are going to describe how the mathematics of *tomography* has become one of the most important applications of mathematics to the problems of keeping you alive. Modern medicine relies heavily on imaging methods, starting with the early use of X-rays at the start of the 20th century.

A CAT scan of the inside of a head.

Essentially these imaging methods take two forms. X-ray and ultrasound methods use a source of radiation that lies outside the body. The radiation is detected after it has passed through the body, and an image constructed from the way it has been absorbed. When X-rays are used, this process is called *computerised axial tomography* or CAT for short. (The word tomography comes from the Greek work *tomos* meaning "cut" or "slice".) This article will look at this process in detail.

Other imaging methods use a source inside the body. These include *magnetic resonance imaging* (MRI), *positron emission tomography* (PET) and *single photon emission computed tomography* (SPECT). These methods have certain advantages over CAT, both in image resolution and in safety, as X-rays can easily damage soft tissue. The basic mathematics behind tomography was worked out by the mathematician Johann Radon in 1917. Much later, in the 1960s Allan McLeod Cormack, working in collaboration with Godfrey Newbold Hounsfield, developed the first practical scanning device, the celebrated EMI scanner. For this work, Cormack won the Noble Prize. Early models could only scan an object the size of a human head, but whole body scanners followed shortly after.

Medical imaging works because of a combination of very careful measurement techniques, sophisticated computer algorithms, and powerful mathematics. It is the mathematics that we will describe here. We will also show that the mathematics of tomography has many other applications, including imaging the atmosphere, detecting land-mines and, slightly more frivolously, solving Sudoku puzzles.

Milk deliveries and Killer Sudoku

Before delving into the depths of medical science, we will start with a simple example which illustrates the principles of tomography, and which has a very nice link to the various types of Sudoku that have become very popular recently. This example involves milk deliveries. Imagine that milk and fruit juice is delivered in bottles that are placed in trays with 9 compartments arranged as a 3 × 3 grid. Each compartment of the tray contains a bottle which may contain milk, juice or be empty. The question is: which type of bottle is in which compartment?

Unfortunately, other trays are above and beneath the one we're interested in, so we can't look down on top of the tray. At first sight it would seem impossible to solve this problem. However, we can peer in through the sides and we can measure how much light is absorbed in different directions. Different types of bottle absorb different amounts of light. Careful measurements have shown that milk bottles absorb 3 units, juice bottles 2 units and empty bottles one unit. If a light beam is shone through several bottles, then this absorption adds up. If, for example, a light beam shines through a milk bottle and then a juice bottle, then 5 units are absorbed. If it passes through three empty bottles then 3 units are absorbed.

In the example below we have indicated the total amount of light absorbed when shining light through each of the rows and each of the columns.

			5
			6
			4
6	3	6	

To solve this puzzle, we must place a bottle with 1,2 or 3 units of light absorption in each compartment, with the sum of the units in the first row equalling 5, in the second row 6 etc. The middle column contains 3 bottles and also absorbs 3 units of light. The only way this can be done is for each compartment of the middle column to contain one empty bottle absorbing one unit of light each. What about the other compartments? Unfortunately we don't have enough information (yet) to solve this puzzle. Here are two different solutions:

3	1	1
2	1	3
1	1	2

2	1	2
2	1	3
2	1	1

We are faced with a rather unusual situation for a mathematician in that we have two perfectly plausible solutions to the same problem. Problems like this are called *ill-posed* and are common in situations where we are trying to extract information from an image. To find out exactly how the bottles are distributed, we need to put in a little extra information. One obvious extra thing we can measure is the light absorbed in the two diagonals of the tray. We do this and find that 6 units are absorbed in the top left to bottom right diagonal, and 3 units in the bottom left to top right diagonal. From this extra piece of information it is clear that the first solution, and not the second, corresponds to the measurements made. It can be shown with a bit of extra maths, that if we can measure the light absorbed in the rows, columns and diagonals exactly, then we can uniquely determine the arrangement of the bottles in the compartments of the tray.

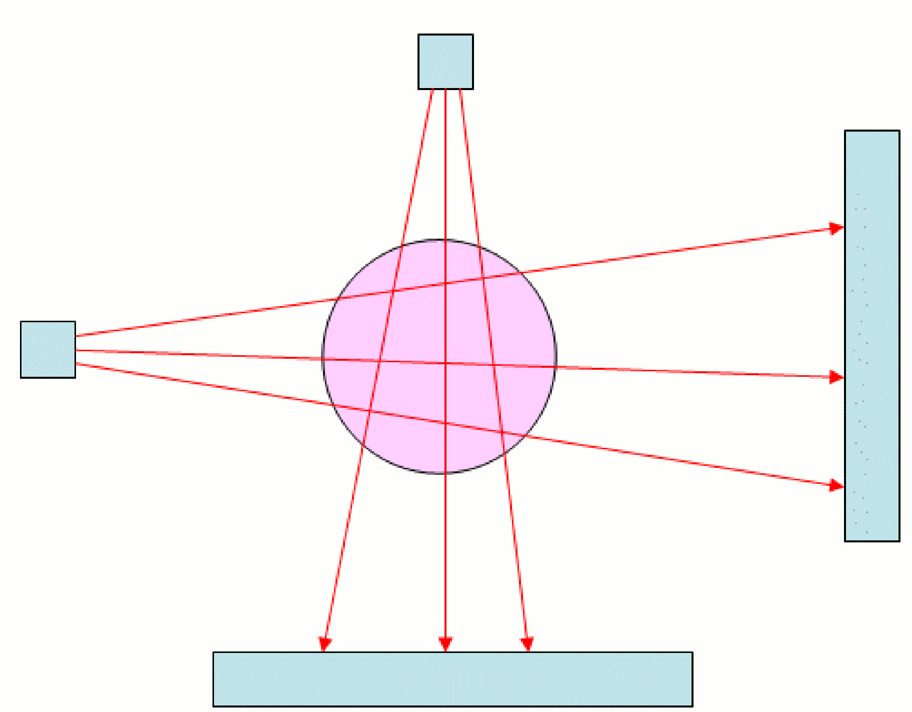
This problem may seem trivial, but it is very similar to the medical imaging problem we will describe in the next section, and shows how important it is to obtain enough information about a situation to make sure that we know what is going on exactly.

If any of this looks familiar to newspaper readers, then it is. *Killer Sudoku* is an advanced version of the popular Sudoku puzzle. In Killer Sudoku, as in Sudoku, the player is asked to place the numbers 1 to 9 in a grid with each number occurring once and once only in each row and column. However, rather than giving the player some starting numbers (as in Sudoku) Killer Sudoku tells you how the numbers add up in certain combinations. This is precisely the same as the problem described above.

CAT and the Radon Transform

Until relatively recently, if you had something wrong with your insides, you had to be operated on to find out what it was. Any such operation carried a significant risk, especially in the case of problems with the brain. However, this is no longer the case; as we described in the introduction, doctors are able to use a whole variety of scanning techniques to look inside you in a completely safe say. A modern Computerised Axial Tomography (CAT) scanner is illustrated on the left.

In this scanner the patient lies on a bed and passes through the hole in the middle of the device. This hole contains an X-ray source which rotates around the patient. The X-rays from this source pass through the patient and are detected on the other side. The level of intensity of the X-ray can be measured accurately and the results processed. The resulting fan of X-rays is illustrated in the following figure (with a conveniently circular patient).



As an X-ray passes through a patient, it is attenuated so that its intensity is reduced. The degree to which this happens depends upon what material the ray passes through: its intensity is reduced more when passing through bone than when passing through muscle, an internal organ, or a tumour. A key step in reconstructing an image of the body from a set of X-ray measurements is to carefully measure exactly how different materials absorb X-rays.

When an X-ray passes through a body, it does so in a straight line, and its total absorption is a combination of the amounts to which it is absorbed by the different materials that it passes through. To see how this happens, we need to use a little calculus. Imagine that the X-ray moves along a straight line and that at a distance s into the body it has an intensity $I(s)$. As s increases, so $I(s)$ decreases as the X-ray is absorbed. Now, if the X-ray travels a small distance δs, its intensity is reduced by a small amount δI . This reduction depends both on the intensity of the X-ray and the *optical density* $u(s)$ of the material. Provided that the distance travelled is small enough, the reduction in intensity is related to the optical density by the formula

$$\delta I = -u(s)I(s)\delta s.$$

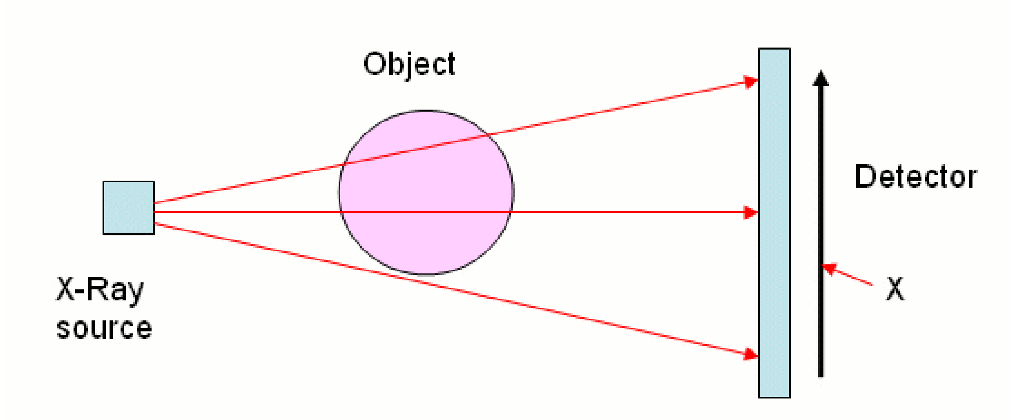
Now, when the X-ray enters the body it will have intensity I_{start} and when it leaves it will have intensity I_{finish}. We can combine all of the contributions to the reduction in the intensity of the X-ray given by all of the parts of the body that it travels through. Doing this, we find that the attenuation (the reduction in the intensity) is given by

$$I_{finish} = I_{start} e^{-R},$$

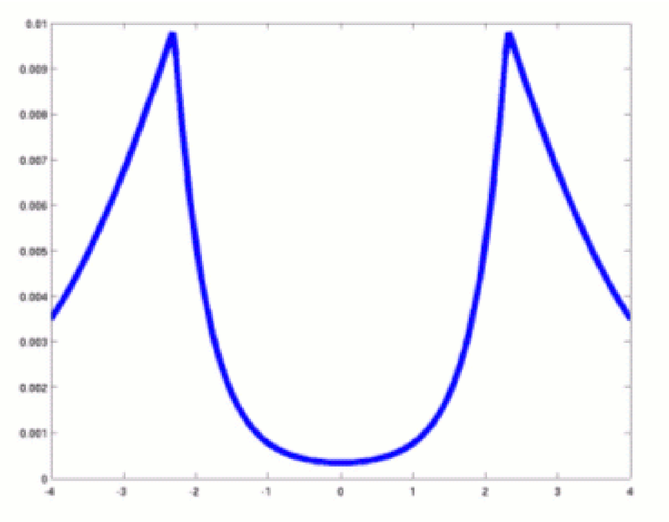
where

$$R = \int u(s) ds.$$

This is the attenuation of one X-ray and it gives some information about the body. Below we see an object irradiated by several X-rays with the intensity of the rays measured on a detector. Here some X-rays pass through all of the object and are strongly absorbed so that their intensity (recorded at the centre of the detector) is low, while others pass through less of the object and are less strongly absorbed. Effectively the object casts a shadow of the X-rays and from this we can work out its basic dimensions. We illustrate this below.

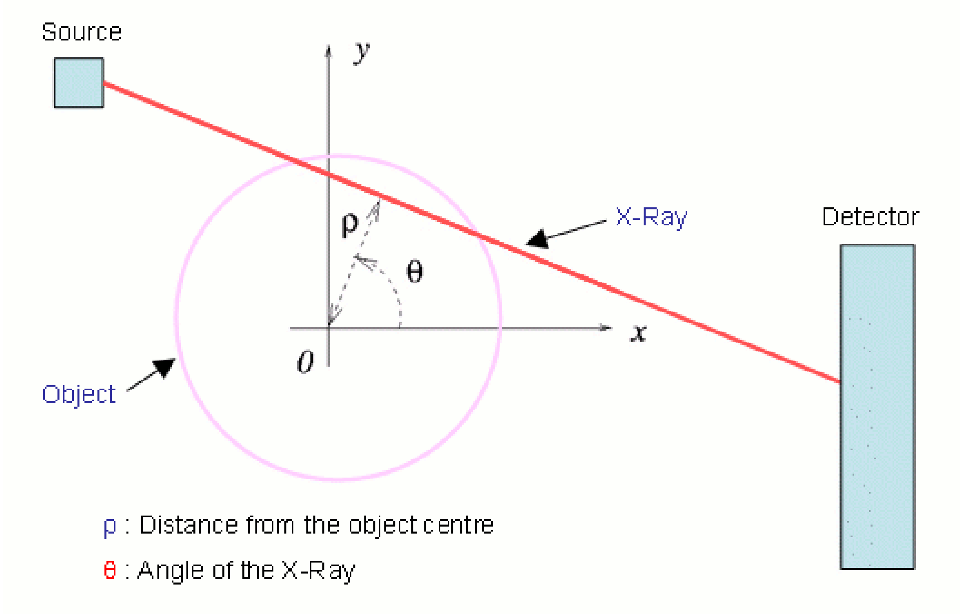


The intensity of the X-ray where it hits the detector depends on the width of object and the length of the path travelled both through the object and the air.



This graph show s the intensity of the rays as they hit the detector. Rays that travel through the full w idth of the object have low est intensity, as w e can see from the dip in the middle of the graph. Rays that just miss the body have the highest intensity, because of all rays that are not absorbed they travel the shortest distance. This is reflected by the tw o spikes of the graph. Tow ards the edges the graph falls off, reflecting the fact that the corresponding rays have travelled a comparatively long distance.

However, the secret to computerised axial tomography is to find out much more about the nature of the object than just its dimensions, by looking at the attenuation of as many X-rays as possible. To do this, we need to think of a number of X-rays at different angles θ and distances ρ from the centre of the object. A typical such X-ray is illustrated below.



This X-Ray will pass through a series of points (x, y) at which the optical density is $u(x, y)$. Using the equation for a straight line these points are given by

$$(x, y) = (\rho\ \cos(\theta) - s\ \sin(\theta), \rho\ \sin(\theta) + s\ \cos(\theta)),$$

where s is the distance along the X-ray. In this case we now have

$$I_{finish} = I_{start}e^{-R(\rho,\theta)},$$

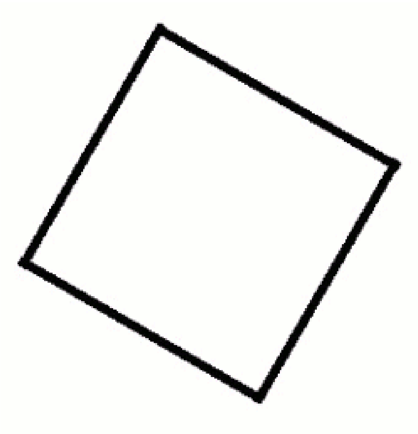
where

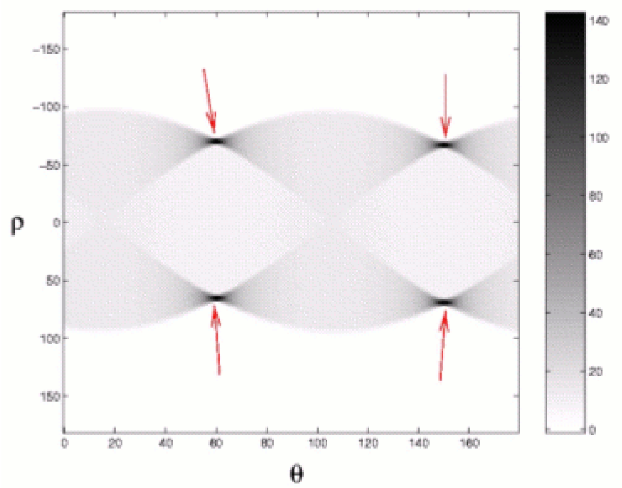
$$R(\rho,\theta) = \int u(\rho\ \cos(\theta) - s\ \sin(\theta), \rho\ \sin(\theta) + s\ \cos(\theta))ds.$$

The function $R(\rho,\theta)$ is called the *Radon transform* of the function $u(x,y)$. The larger R is, the more an X-ray of this particular orientation is absorbed. This transformation lies at the heart of the CAT scanners and all problems in tomography. It was first studied by Johann Radon in 1917. (Radon is also famous for some very important discoveries related to the branch of mathematics called *measure theory*, which is the basis of integration.) By measuring the attenuation of the X-rays from as many angles as possible, it is possible to measure this function to a high accuracy. The big question of mathematical tomography is then the problem of *inverting* the Radon transform, in other words

Can we find the function $u(x,y)$ if we know the function $R(\rho,\theta)$?

Incidentally, this is exactly the same problem faced by our milk deliverer in the previous section. The short answer to this question is YES, provided that we can make enough accurate measurements. A complete explanation of this, together with a quick way of calculating $R(\rho,\theta)$, is given in this section (for the brave). However, a quick motivation will be given by the following example. In the two figures below we see on the left a square and on the right its Radon transform in which the large values of $R(\rho,\theta)$ are shown as darker points.





The key point to note in these two images is that the four straight lines making up the sides of the square show up as points of high intensity (arrowed) in the Radon transform. The arrowed points give both the orientation of the lines and their distances from the centre of the square. The reasons that lines give large values for R at certain points is that an X-ray passing straight through a line is strongly absorbed, whereas one which misses it, even slightly, is hardly absorbed at all.

Basically the Radon transform is good at finding straight lines in an image. One method for finding $u(x,y)$, called the *filtered back projection algorithm*, works (roughly) by assuming that the original image is made up of straight lines and drawing those corresponding to the high values of R. This method is fast but not particularly accurate. However, it is possible to find $u(x,y)$ accurately and quickly, and algorithms to do this are implemented in the scanning devices. The original development of such devices uses a mathematical object known as *Fourier transform* to invert Radon transforms. If you're up for some serious maths, read the section on how this is done. Most of the maths here is university level, but the section contains some lovely mathematical ideas.

Listen to our podcast on the Fourier transform.

Tomography has many applications quite different from those in medicine. An interesting example comes from archaeology, where tomography was used to determine the cause of Tutankhamen's death. A CAT scan of the mummy revealed a swelling in the knee, indicating that death was the result of a massive infection. The cause of this was probably an injury inflicted by a fall. Whether

Tutankhamen was pushed or fell by accident, however, will have to remain a mystery which even a CAT scanner cannot solve.

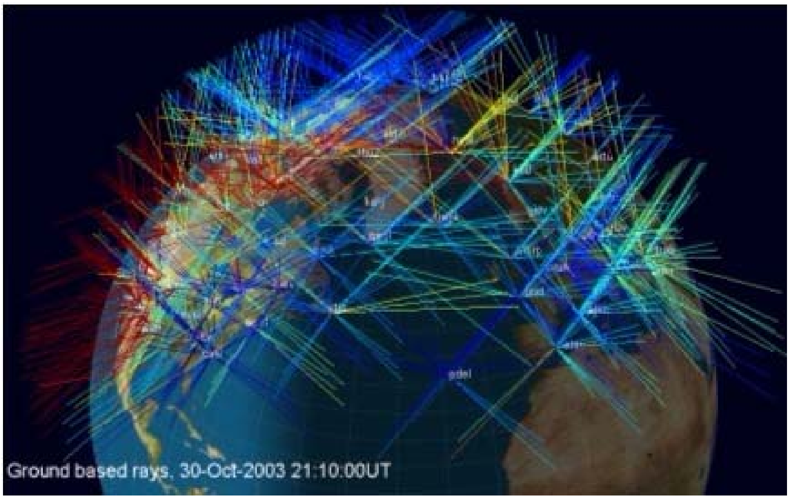
More generally, we can apply tomography to any problem where we have information about the average of a function along a straight line. It can also be used to find evidence for straight lines in an image (such as the edge of an object). We will now describe two examples of how tomography is used.

Tomography, GPS and how to land an aircraft safely

Orbiting the Earth are a large number of GPS satellites that are transmitting radio signals down to the ground. If you can detect the signals and find the phase difference between the signals from several different satellites, then you can work out your location with a high degree of accuracy. GPS positioning methods are very widely used by aircraft navigation systems, SATNAV devices and hikers. However, one of the problems with this system is that variations in the *ionosphere* (the upper part of the Earth's atmosphere) can affect the radio signals and change their phase by small amounts. This phase change can lead to errors in the position given by the GPS system. These are not very large and are perfectly acceptable for navigating. However, when landing an aeroplane it is vital that its height is known to very high precision and even small GPS errors can have large consequences. Here an accurate understanding of the state of the ionosphere is essential.

There are many other reasons why understanding the ionosphere is important. Chief amongst these is that fact that the ionosphere has a very significant effect on the propagation of radio waves and on communication in general. Roughly speaking, radio waves can bounce off the ionosphere, greatly increasing the range of a radio transmitter.

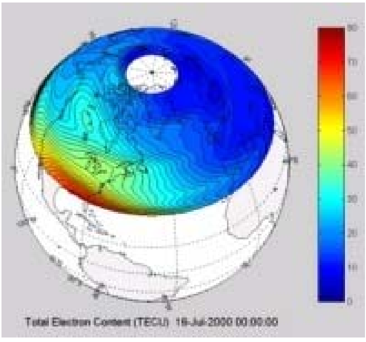
Remarkably, it is possible to monitor the state of the ionosphere using tomography. In the problem of imaging a patient we shone X-rays through their body. To image the ionosphere we use the transmissions from the GPS satellites. These form a very convenient set of "straight lines" passing through the ionosphere. The paths that they take are shown in the figure below.

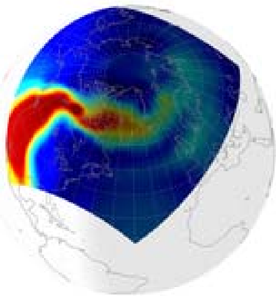


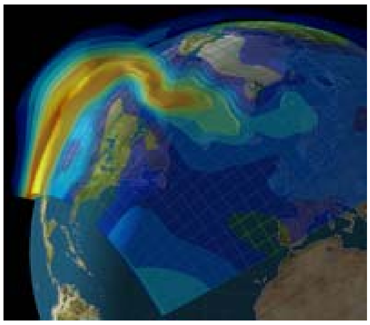
The phase of the radio waves is affected by the electron content of the atmosphere, so that the total change in the phase is proportional to the integral of the electron density along the ray path. If we can measure these phase changes, then we can estimate the electron density integrals and work out the Radon transform of the electron density. We seem to be in exactly the same situation as in the medical imaging problem and hence able to work out the electron density at any point in the atmosphere.

Well, not quite. There are two big differences between this problem and the CAT problem. Firstly, the satellites are usually moving relative to the Earth. Secondly, there are large parts of the Earth's surface where we cannot make any measurements. These include the oceans, where there are no receivers for the satellite signals, and the poles, which do not have satellites orbiting above them. Thus we have a lot less information than we had in the case of the CAT scanner. This means that we are often in the situation of the milk deliverer who couldn't distinguish between two different arrangements of milk bottles, each of which led to the same set of measurements.

To get round this problem in the case of the ionosphere, we have to use a-priori information about the state of the ionosphere, or in other words a reasoned guess of what the solution should look like. This will allow us to reject one solution which doesn't look like this guess and to choose the solution which looks as much like the guess as possible. Fortunately, we understand the physics of the ionosphere well enough for our reasoned guess to be pretty close to the truth. By doing this (together with some other clever refinements) it is possible to use tomography to find the state of the ionosphere. In the figures below we illustrate a calculation (using the MIDAS software developed at the University of Bath) of an ionospheric storm (in red) developing over the southern part of the USA.

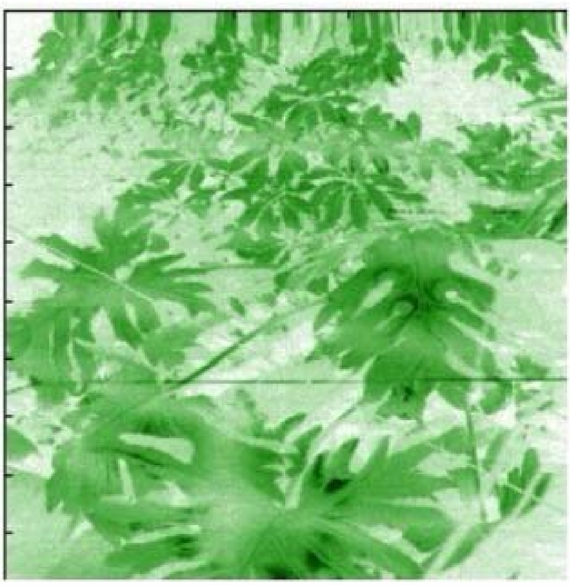






Detecting land-mines

Anti-personnel land-mines are one of the nastiest aspects of the modern warfare. They are typically triggered by almost invisible trip-wires attached to the detonators. Any algorithm for the detection of trip-wires must work quickly and not get confused by the leaves and foliage that obscure the wire. An example of the problem that such an algorithm has to face is given in the figure below, in which some trip-wires are hidden in an artificial jungle.



Can you find the three trip-w ires hidden in this image?

Finding trip-wires involves finding partly obscured straight lines in an image. Fortunately, just such a method exists; it is the Radon transform! For the problem of finding the trip-wires we don't need to find the inverse, instead we can apply the Radon transform directly to the image. Of course life isn't quite as simple as this for real images of trip-wires, and some extra work has to be done to detect them. In order to apply the Radon transform the image must first be pre-processed to enhance any edges. Following the application of the transform to the enhanced image a threshold must then be applied to the resulting values to distinguish between true straight lines caused by trip-wires (corresponding to large values of R) and false lines caused by short leaf stems (for which R is not quite as large).

Following a sequence of calibration calculations and analytical estimates with a number of different images, it is possible to derive a fast algorithm which detects the trip-wires by first filtering the image, then applying the Radon transform, then applying a threshold and then applying the inverse Radon transform. The result of applying this method to the previous image is given on the left, with the three

detected trip-wires are highlighted.

Note how the method has not only detected the trip-wires, but, from the width of the lines, an indication is given of the reliability of the calculation.

Maths truly does save lives!

You might also want to listen to our podcast on the Fourier transform.

About the authors

Chris Budd is Professor of Applied Mathematics at the University of Bath, and Chair of Mathematics for the Royal Institution. He is particularly interested in applying mathematics to the real world and promoting the public understanding of mathematics.

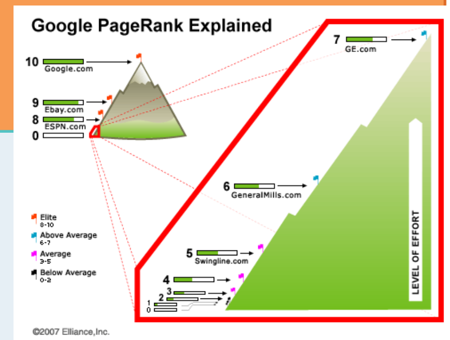
He has recently co-written the popular mathematics book *Mathematics Galore!*, published by Oxford University Press, with C. Sangwin.

Cathryn Mitchell is Professor of Electronic and Electrical Engineering and EPSRC Research Fellow at the University of Bath. She is interested in all sorts of tomography problems ranging from medical imaging to space physics.

Math Matters

Apply It.

The math behind... Google PageRank™



Technical terms used:

Graph theory, random walk, Markov chain, linear system, eigenvector, power iteration

Uses and applications:

PageRank™ is one of many factors that influence what pages appear at the top of the list of results of a Google™ search. The PageRank value of a webpage is a measure of that page's relative importance according to the hyperlink structure of the surrounding web.

How it works:

Imagine a person surfing the web by randomly clicking on hyperlinks to travel between pages. The path of this "random surfer" can be viewed as a random walk on the vertices of the web graph and can be described mathematically as a trajectory of the Markov chain whose transition probabilities are determined by the hyperlink structure of the web. The likelihood that, in the long run, the surfer ends up on a specific page is entirely dependent on this hyperlink structure. In general, this long-term likelihood is called the stationary distribution of the Markov chain, but in the context of a random surfer traversing the web graph it is called PageRank.

Under certain assumptions about the structure of the web graph, PageRank turns out to be the unique unit eigenvector corresponding to the largest eigenvalue of the hyperlink matrix. In practice, this eigenvector can be computed via the power iteration, a common technique in linear systems theory.

Google originally applied the PageRank algorithm to a web of 24 million pages in 1998. By 2014, the size of the indexed web had grown thousand-fold to the order of tens of billions. As the web continues to grow, challenges arise in the computation of PageRank. Although these challenges are somewhat mitigated by improving computer technology, they are also being addressed through academic research on algorithm efficiency. Recent approaches include a distributed randomized updating of PageRank within a web-aggregation framework.

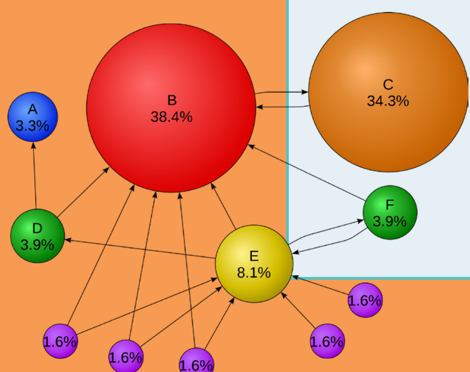
Interesting fact:

While the term PageRank is self-referential, describing a measure of rank associated with each page in the indexed web, it is also an intentional play on the name of Google co-founder and CEO, Larry Page.

References:

[1] S. Brin and L. Page, The anatomy of a large-scale hypertextual web search engine, Computer Networks and ISDN Sys. 30(1-7), 107-117 (April 1998).

[2] H. Ishii and R. Tempo, The PageRank problem, multiagent consensus, and web aggregation: A systems and control viewpoint, IEEE Control Sys. Mag. 34(3), 34-53 (June 2014).



Submitted by Cody Clifton, University of Kansas, Third Place, Math Matters, Apply it! Contest, February 2015.

Statistician Professor Terry Speed wins 2013 PM's Prize for Science

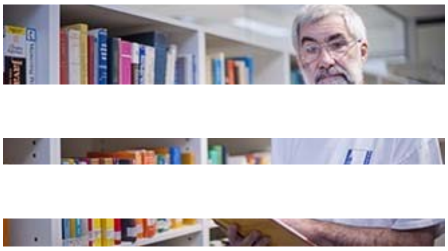
URL: http://www.wehi.edu.au/news/statistician-professor-terry-speed-wins-2013-pm%E2%80%99s-prize-science

Home

Statistician Professor Terry Speed wins 2013 PM's Prize for Science

30 October 2013

Statistician Professor Terry Speed from Melbourne's Walter and Eliza Hall Institute has been awarded the 2013 Prime Minister's Prize for Science for his influential work using mathematics and statistics to help biologists understand human health and disease.



Bioinformatics Professor Terry Speed won the 2013 Prime Minister's Prize for Science.

The Prime Minister's Prize for Science is Australia's highest award for excellence in science research, and was presented to Professor Speed tonight at a ceremony at Parliament House. The award recognises the significant importance of bioinformatics in modern biomedical science.

Bioinformatics is a relatively new branch of science that combines maths, statistics and computer science to solve complex biological problems. Over the course of his 44-year career, Professor Speed has developed mathematical and statistical tools that enable biologists to make sense of the vast amounts of information generated by rapidly advancing (next-generation) genetic technologies.

Bioinformatics has made it possible to look at hundreds of genes in a DNA sequence at once to understand the genetic changes involved in complicated diseases such as cancers, and is integral to the genomics revolution that is driving the sequencing of whole genomes in record times. Professor Speed has developed tools to identify genes that are responsible for different traits, diseases or cancers by sifting through these enormous volumes of data.

In addition to developing tools to help biologists analyse and explain their results, Professor Speed is working with biologists to determine the genetic traits that make normal and cancerous cells different; developing tools to help determine if thyroid growths are benign or cancerous; and determining the risk children in malaria-endemic countries have of developing clinical malaria, which helps to inform prevention and treatment strategies.

Professor Speed said it was a great honour to receive the Prime Minister's Prize for Science. "Australia is full of many amazing and talented researchers, so it is humbling to be recognised in this way," he said. "Science is a collaborative effort and I would like to thank the many students, postdocs and colleagues that have supported me throughout my career. In addition, I would like to thank my wife, Sally, whose love and support over the past 50 years has enabled me to pursue my research with passion."

Walter and Eliza Hall Institute director Professor Doug Hilton said he was delighted Professor Speed's global contributions to bioinformatics and biology had been recognised by the Australian Government. "Terry is a champion for statistics and bioinformatics, and has been instrumental in educating the next generation of bioinformaticians," Professor Hilton said. "Not only is his scientific acumen first-class, he is a compassionate mentor and a true leader, demonstrated by his strong support for gender equality."

Professor Speed is head of the institute's Bioinformatics division and he still heads a small group at the University of California, Berkeley, US. He is also involved in The Cancer Genome Atlas project, an international collaboration that is identifying the genetic changes responsible for more than 20 types of cancer, in order to develop new diagnostics and treatments.

The 2013 Prime Minister's Prize for Science is the latest in a string of awards for Professor Speed. In May, he was elected a Fellow of the Royal Society, UK, while in 2012 he was the recipient of the Victoria Prize for Science and Innovation and won the Thomas Reuters Citation Award in Biochemistry and Molecular Biology for being the most cited Australian researcher in that field for the past decade. He also received the inaugural National Health and Medical Research Council (NHMRC) Achievement Award for Excellence in Health and Medical Research in 2007, an NHMRC Fellowship in 2009 and the Australian Government Centenary Medal in 2001.

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Last modified: Mon, 22/02/2016 - 5:05pm

Other Titles in Applied Mathematics

Wavelets: Tools for Science and Technology

Authors: **Stéphane Jaffard** , **Yves Meyer** and **Robert D. Ryan**

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University of Paris XII, Creteil, France
Yves Meyer:
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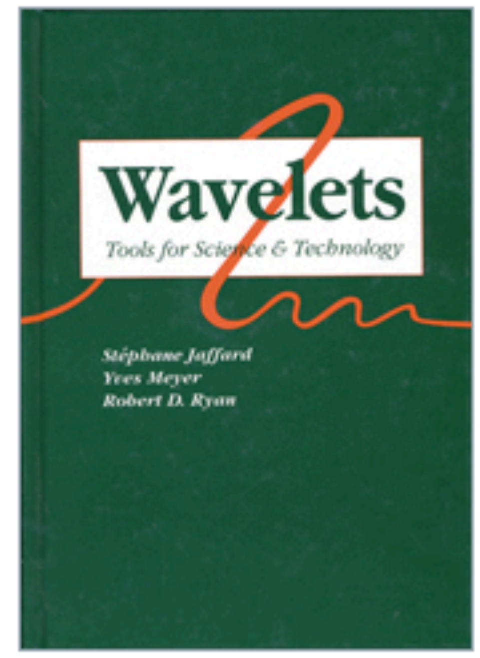
Robert D. Ryan:
Paris, France

DOI: http://dx.doi.org/10.1137/1.9780898718119

Permalink: http://dx.doi.org/10.1137/1.9780898718119
Keywords: wavelets, data compression, fractals, image processing, turbulence



- Hide Description

This long-awaited update of Meyer's *Wavelets: Algorithms & Applications* includes completely new chapters on four topics: wavelets and the study of turbulence, wavelets and fractals (which includes an analysis of Riemann's nondifferentiable function), data compression, and wavelets in astronomy. The chapter on data compression was the original motivation for this revised edition, and it contains up-to-date information on the interplay between wavelets and nonlinear approximation. The other chapters have been rewritten with comments, references, historical notes, and new material. Four appendices have been added: a primer on filters, key results (with proofs) about the wavelet transform, a complete discussion of a counterexample to the Marr-Mallat conjecture on zero-crossings, and a brief introduction to Hölder and Besov spaces. In addition, all of the figures have been redrawn, and the references have been expanded to a comprehensive list of over 260 entries. The book includes several new results that have not appeared elsewhere.

Title Information

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Book Code: OT69

Series: Other Titles in Applied Mathematics

Pages: xiii + 245

Buy the Print Edition

Wavelet analysis---an exciting theory at the intersection of the frontiers of mathematics, science, and technology---is a unifying concept that interprets a large body of scientific research. In addition to its intrinsic mathematical interest, its applications have serious economic implications in the areas of signal and image compression. For these expanding fields, this book provides a clear set of concepts, methods, and algorithms adapted to a variety of applications ranging from the transmission of images on the Internet to theoretical studies in physics. The use of wavelet-based algorithms adopted by the FBI for fingerprint compression and by the Joint Photographic Experts Group for the new JPEG-2000 compression standard confirms the success of this theory.

The authors present with equal skill and clarity the mathematical background and major wavelet applications, including the study of turbulence, fractal objects, and the structure of the universe. Never before have the historic origins, the algorithms, and the applications of wavelets been discussed in such scope, providing a unifying presentation accessible to scientists and engineers across all disciplines and levels of training.

Written specifically for scientists and engineers with diverse backgrounds, the material is presented in a manner that will appeal to both experts and nonexperts alike. This book is a valuable tool for anyone (from graduate student to expert) faced with signal or image processing problems. It also answers the question, "What are wavelets?"

The first seven chapters trace the historical origins of wavelet theory and describe the different time-scale and time-frequency algorithms used today under the term "wavelets." Specific examples include the application of wavelet techniques to FBI fingerprint compression problems and the use of wavelets in the new JPEG standard for still image compression. Applying wavelet analysis methods to signal and image processing, fractals, turbulence, and astronomy is covered in the balance.

- Show Excerpt

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Announcement

by the Federal Ministry of Education and Research (BMBF) of regulations governing funding of selected key areas of basic scientific research in the field of "Mathematics for innovations in industry and services"

of 04/10/2012

Mathematical solutions have come to play a crucial role in nearly every field of technology. Mathematics is an interdisciplinary field whose significance is not limited to basic research. Because of their universal applicability, advances in mathematics have the potential to generate innovations across the entire spectrum of technologies addressed by the Federal Government's High-Tech Strategy. The aim of the BMBF funding activity "Mathematics for innovations in industry and services" is to take advantage of the leverage created by mathematics to solve some of the challenges facing society.

1. Funding purpose, legal basis

1.1 Funding purpose

The Federal Ministry of Education and Research (BMBF) intends to fund research and development projects in the field of "Mathematics for innovations in industry and services".

Applied mathematics, especially the field of mathematical modelling, simulation and optimization, are key factors of innovations in industry and the service sector related to the fields of action of the Federal Government's High-Tech Strategy 2020. Increasing cross-linkage of various subfields of mathematics at the basic level is leading to ever more efficient solution processes. The efficient transfer into practice of basic scientific findings in applied mathematics is one important means of strengthening Germany's position as a key location of innovation. Methods practised in applied mathematics can help to sustainably optimize processes, decision-making, services and products, or even make them possible in the first place. This includes the optimization of production processes and of transport, energy or communications networks, as well as the implementation of mathematical methods as the basis for simulation and planning in automotive engineering in the high-tech development of materials. They are also relevant to the development of space technology and basic innovations in pharmaceutical research and medicine.

The aim of the funding measure is to implement mathematics to make an effective contribution to solving one or more of the societal challenges identified in the High-Tech Strategy of the Federal Government. It is designed to promote projects in mathematical research that require the close collaboration of basic research and businesses to develop new products, processes and services that can be exploited on the market. Its focus is on application-oriented research that produces the greatest possible benefit.

Other objectives are to expand on Germany's high international ranking in applied mathematics, to make intensive use of and disseminate basic scientific findings, to enhance the attractiveness of Germany as a research base for top researchers from abroad and thus strengthen Germany's international competitive edge, and to foster sustainable development in both the economy and society.

Young research talent should be promoted in a targeted way to achieve these aims. Providing intensive support for young scientists and the targeted promotion of interdisciplinary topics in mathematics will enhance the innovation effect of research and accelerate the use of its results.

1.2 Legal basis

Project grants will be awarded in accordance with the present funding regulations, the BMBF's standard terms and conditions for grants on an expenditure or cost basis and the administrative regulations under section 44 of the Federal Budget Code (BHO). There is no legal entitlement to a grant. The funding provider will take a decision after due assessment of the circumstances and within the framework of the budget funds available.

2 Object of funding

Funding in the “Mathematics for innovations in industry and services” programme aims at developing solutions in applied mathematics that can be used to solve challenging, practical problems.

The funding measure focuses especially on activities in the field of mathematical modelling, simulation and optimization (MMSO). Priority will be given to a combination of novel mathematical methods or results from MMSO with relevance to applications in the fields of action of the Federal Government's High-Tech Strategy (http://www.hightech-strategie.de/de/).

Research in the following mathematical methods and fields of application is expected:

- Modelling, simulation and optimization under uncertainty
- Combined multi-physics systems
- Modelling and numerics of multi-scale and hybrid systems (including effective illustration via modern computer architecture)
- Modelling and simulation of complete process chains
- Model reduction and adaptation
- High-dimensional problems
- Real-time processes
- Visualization and data analysis

Research results must be especially appropriate to address select practical problems. The combination of methodical approaches to different dimensions of a problem (e.g. deterministic and stochastic, linear and non-linear or continuous with other discrete methods) is very significant in this context.

High priority is to be given to all the aspects of mathematical modelling, especially to the mathematically motivated identification, validation and discrimination of models, or the (meta-) modelling of mathematical optimization problems.

Research projects in MMSO with a dimension applicable to (personalized) medicine, systems biology and the energy system (network optimization) are expressly desired.

Priority will be given to larger collaborative projects made up of research groups from different disciplines and which involve partners from practice. The major goals of research must be the applicability of future mathematical technologies to different fields and the transfer of mathematical knowledge into practice.

A high degree of integration of junior researchers (post-doctoral scholars, junior professors) acting as leaders of projects or sub-projects in the collaborations is expressly desired. It is expected that the project leaders will make a special effort to involve young scientists. Junior researchers are expected to launch initiatives in exploratory and relatively risky fields of MMSO. The mathematical innovation and the potential of new ideas are considered significant factors in the collaboration with young scientists.

The BMBF aims to increase the share of researchers returning from abroad in research funding. Young scientists who have spent a significant amount of time doing research abroad are especially encouraged to take part in the funding activity "Mathematics for innovations in industry and services” through a German research institution.

3. Recipients of funding

Research proposals may be submitted by institutions of higher education and non-university research institutions based in Germany. Research establishments which receive joint basic funding from the Federal Government and the *Länder* can only be granted project funding supplementary to their basic funding for additional expenditure under certain preconditions.

4 Prerequisites for funding

The collaborative projects are to develop theoretical principles, mathematical-scientific modelling and solution methods which can be demonstrated through exemplary execution of concrete assignments given by partners in industry. The proposed projects must be structured in such a way that real progress and practicable results can be achieved for the industry partner within the established funding period. Although applicants must establish close cooperation with business enterprises as application partners, there are no provisions to provide funding to said enterprises. Participating partners in industry must submit a Declaration of Intent to cooperate with the research institutions which states the commercial use of the anticipated project results.

Cooperation between the partners in a collaborative project must be laid down in a cooperation agreement. Before a funding decision can be taken, the cooperation partners must prove that they have reached a basic agreement on certain criteria stipulated by the BMBF. Details can be found in the BMBF’s form 0110.

https://foerderportal.bund.de/easy/easy_index.php?auswahl=easy_formulare&formularschrank=bmbf#t6

Funding for projects in the field of "Mathematics for innovations in industry and services” is granted based on the following requisite (a.-g.) and favourable (h.-k.) conditions and principles:

a. Research issues must address at least one of the fields of action in the High-Tech Strategy of the Federal Government (see http://www.hightech-strategie.de/de/350.php)
b. Concrete applications (assignments from a partner in industry or service sector, real data) for which there is proven demand must be demonstrated.
c. Interested partners in industry and the service sector are involved in project work.
d. New or newly developed approaches, methods or processes in mathematics research (MMSO) must be applied in the completion of tasks assigned by industry and the service sector.
e. The combination of methodical approaches to different dimensions of a problem (e.g. deterministic and stochastic, linear and non-linear or continuous with other discrete methods) is very significant. The coupling of models in the multiphysics or multi-scale systems must be highlighted.
f. The envisaged solution to the selected practical problem is representative of a wider category of tasks and will facilitate broader application of results.

g. The specific requirements for developing the necessary mathematical models are met by the project collaboration.
h. The project selection procedure grants high priority to the targeted integration of young scientists.
i. Dissemination of mathematical methods in a number of new fields is desirable. Details of creative and sustainable strategies for the dissemination of methods and results are provided in the application for funding.
j. Projects are open to building research networks (informal alliances of collaborative projects).

In their own interest, applicants should familiarize themselves with the EU's Research Framework Programme in the context of the envisaged national project. They should check whether the intended project includes specific European components which make it eligible for exclusive EU funding. Furthermore, they should check whether an additional application for funding can be submitted to the EU in the context of the proposed national project. The result of such checks should be described briefly in the national project application.

5. Type, scope and rates of funding

Funds will be awarded in the form of non-repayable project grants.

Grants for universities, research and science institutions and similar establishments will be calculated on the basis of the eligible project-related expenditure (grants for Helmholtz centres and the Fraunhofer Gesellschaft (FhG) will be calculated on the basis of the project-related costs eligible for funding), up to 100% of which can be covered in individual cases.

6. Other terms and conditions for funding

The *Allgemeine Nebenbestimmungen für Zuwendungen zur Projektförderung* (ANBest-P) (General Auxiliary Conditions for Grants Provided for Projects on an Expenditure Basis) and the *Besondere Nebenbestimmungen für Zuwendungen des BMBF zur Projektförderung auf Ausgabenbasis* (BNBest-BMBF 98) (Special Auxiliary Terms and Conditions for Funds Provided by the BMBF for the Promotion of Projects on Expenditure Basis) will form part of the notification of award of grants on an expenditure basis.

The *Nebenbestimmungen für Zuwendungen auf Kostenbasis des BMBF an Unternehmen der gewerblichen Wirtschaft für Forschungs- und Entwicklungsvorhaben* (Auxiliary Terms and Conditions for Funds Provided by the BMBF to Commercial Companies for Research and Development Projects on a Cost Basis – NKBF 98) will be part of the notification issued to research institutions of award for grants on a cost basis.

7. Procedure

7.1 Involvement of a project management organization and request for documents

The BMBF has entrusted the following project management organization with implementing the funding measure:

Projektträger DESY
Deutsches Elektronen-Synchrotron
Notkestraße 85
22607 Hamburg

Phone: +49 (0) 40 / -8998 -3702
Fax: +49 (0) 40-8994-3702 Internet: http://pt.desy.de

Please contact:
Nadja Häbe • Phone: +49 (0) 40-8998-5651 • E-Mail: nadja.haebe@desy.de and
Dr. Marc Hempel • Phone: +49 (0) 40-8998-3991 • E-Mail: marc.hempel@desy.de.

Application forms, guidelines, information for applicants and the auxiliary terms and conditions for the award of grants are available online at http://foerderportal.bund.de/, "Formularschrank BMBF“.

7.2. Application procedure

The application procedure consists of two phases. In a first step a project outline as per Nr. 7.2.1 must be submitted. The second step may require submission of a formal application for funding as per Nr. 7.2.2.

7.2.1 Submission and selection of project outlines

In the first phase, assessable project outlines are to be sent by the envisaged coordinator to the appropriate project management organization in written and electronic form by

10 December 2012

at the latest.

Project outlines must be drawn up online via the pt-outline Internet portal:

https://www.pt-it.de/ptoutline/application/mathematik2013

You may make a binding submission of your project outline by clicking on “Control and Submission”. Please send a signed copy of the outline to the project-managing agency.

The submission deadline is not a cut-off deadline. However, it may not be possible to consider project outlines received belatedly.

A legal claim to funding cannot be derived from the submission of a project outline.

The projects should be designed to run for three years and be oriented along concrete milestones. Targets, solutions and major objectives of every collaborative project must be detailed in a document of about 15 pages. Project outlines must also provide details about participating project partners, particularly about participating businesses which intend to develop project results for commercial use and practical application. Furthermore, the costs associated with the preparation of the planned project and required funding amount must be identified.

The project outlines must include a description which is structured along the following lines:

1. **Relevance of programme:** The work programme and goals of the project are clearly relevant to the funding measure. The tasks and objectives of the project are distinct from similar projects of the German Research Association (e.g. MATHEON), the Federal Government or the EU in their respective research programmes, and it complements existing programmes.
2. **Contribution to funding measure (general, overarching use):** The project makes a tangible contribution to at least one of the fields of action of the High-Tech Strategy 2020 of the Federal Government and towards strengthening the international competitiveness of the German economy. There is a clear connection to the considerations and requirements of this call for proposals.
3. **State of the art in research and technology:** There is demonstrable compliance with international state of the art in research. There is no known solution (also at international level) to solving the assignment given by the business partner.
4. **Formulation of the problem:** The tasks and goals of the project are clearly defined from both the user perspective and in terms of mathematical research and development.
5. **Benefit for science:** The mathematical process which is proposed as a solution to the task has yet to be developed, or is not readily available. Extensive mathematical research must still be done. The envisaged results are significant for the field of applied mathematics.
6. **Benefit for partner in industry, commercialization of results:** The project partner from industry and the service sector can guarantee the exploitation of envisaged results. Exploitation of results will result in a strengthening of the industry partner's position on the market and to creation of high-quality jobs. The industry partner must expressly declare his interest in the execution of the joint project in a Declaration of Intent that includes a statement on commercialization prospects, which is addressed to the project coordinator.
7. **Work programme, cost schedule, timetable:** The work programme is clearly outlined (in tabular form) and proposes alternative solutions at critical points (milestones). Initial mathematical model approaches and working hypotheses exist. The collaborative project is able to complete its (mathematical) work successfully within the research time frame and within budget.

   An itemized account of expenditures for staff (including number of post-docs/Ph.D students) and physical resources is required.
8. **Inclusion of junior researchers:** Details of whether and how junior researchers will be included in the proposed project must be provided.
9. **Coordination and resources:** The planned consortium has named a project coordinator; its members are competent to carry out their respective tasks. The funding applied for is essential to the execution of the collaborative project through work done by project partners.

Applicants are advised to contact the relevant project management organization before submitting their documents.

The project proposals submitted will compete against each other. The project outlines are evaluated by a review board which is appointed by the Federal Ministry of Education and Research and which assesses submissions according the requirements identified herein and in line with the prerequisites for funding listed in Section 4 a.–j. above. Project ideas which are suitable for funding will be selected on the basis of the evaluation. Applicants can expect to receive notification of the results of the selection procedure in **mid-January 2013.**

7.2.2 Submission of formal applications for funding and decision-making procedure

In the second phase, project coordinators whose project outlines have received a positive evaluation will be invited to submit a formal application for funding by **15 March 2013** at the latest. The project will be decided on after a final evaluation.

Applications must be submitted through the electronic application system "easy-online" https://foerderportal.bund.de/easyonline/.

When completing the application, click on "Neues Formular" in the menu on the left and then select the funding programme (Fördermaßnahme) "Mathematik2013".

Funding is expected to start on **1 July 2013**.

Approval and payment of and accounting for the funds as well as proof and examination of proper use and, if necessary, revocation of the award and reclaiming of the funds awarded are governed by the administrative regulations pertaining to section 44 of the Federal Budget Code (BHO) and sections 48 to 49a of the Administrative Procedure Act (VwVfG) unless deviation is permitted under the present funding regulations.

8 Entry into force

These funding regulations will enter into force on the day of their publication in the Federal Gazette (Bundesanzeiger).

Bonn, 4 October 2012
Federal Ministry of Education and Research

Dr. Heike Prasse

As part of the vision for a national research centre, the Australian Mathematical Sciences Institute (AMSI) supports the need for a residential research station as an element of the larger plan for an innovative infrastructure platform with multiple nodes. AMSI endorses the forward move by The University of Melbourne and Monash University in creating MATRIX. This content was provided by MATRIX.

MATRIX

Launched in May 2016 MATRIX (www.matrix-inst.org.au) is Australia's first international research institute for the mathematical sciences. MATRIX is focussed on extending high quality mathematics training by providing intensive **residential** research programs, and encouraging collaborations between groups of mathematicians leading to transformative ideas and discoveries. These informal collaborations, in the past, have led and contributed to important industrial applications such as the Internet, WI-FI, GPS and online-banking.

MATRIX is start up national research infrastructure for the benefit of, and endorsed by, the national research community in the mathematical sciences. While established through a joint partnership between the University of Melbourne and Monash University, with seed funding from the ARC Centre of Excellence for Mathematical and Statistical Frontiers (ACEMS), it needs sustained government funding to be scaled up to deliver on its potential as a national facility.

MATRIX provides intensive residential mathematical programs at the MATRIX House, a residential location in Creswick, Victoria.

Mathematics and statistics are inherently international disciplines, and international exposure of students and early career researchers is essential to prepare them for the global market in the growth demand area of science and technology. Through many international examples it is proven that a reputable Australian residential research institute in the mathematical sciences is a very attractive proposition for leading overseas researchers to spend significant time in Australia. Such longer term visits during interactive research programs are essential for early career researchers to build new international collaborations and through face-to-face interactions quickly get to the forefront of international research leading to the identification and development of new areas within mathematical sciences.

Almost every OECD country has one or more research institutes in the mathematical sciences. Well known examples include the

- Mathematical Sciences Research Institute (MSRI) in Berkeley
- The Simons Center for Geometry and Physics in Stony Brook
- The Banff International Research Station in Canada
- ``Oberwolfach" and the Hausdorff Institute in Germany
- L'Institut Henri Poincare in France
- Mittag-Leffler in Sweden
- The Lorentz Center in Leiden
- ``Bedlewo" in Poland

- The National Institute of Pure and Applied Mathematics (IMPA) in Brazil
- The Isaac Newton Institute for Mathematical Sciences in Cambridge

It is MATRIX's vision to ensure that intensive residential research programs enhance Australia's international reputation as a leader in mathematical sciences, contribute to national and state science and innovation policies and provide the opportunity to explore collaborations with industry.

With time and upgraded facilities, longer programs can be offered by MATRIX which will contain embedded short conferences or lecturer series with the aim of enticing key academic and industry leaders in the mathematical sciences field as keynote speakers. This will also aid in the promotion of the mathematical sciences through the development of continuing to establish an 'inspiring women in mathematics network'.

MATRIX believes Government should explore philanthropy as well as partnerships with industry and universities to jointly fund a venue and operational budget for a residential research institute in the mathematical sciences. Such funding models occur in the US and would be supported by the Australian mathematical sciences research community.

MATRIX believes that research in the mathematical sciences is a creative enterprise and real breakthroughs require new ways of thinking at highly abstract levels.

Intensive research programs lasting several weeks or months at **residential** research stations constitute one of the most successful pieces of infrastructure for fostering innovative and internationally competitive research in the mathematical sciences. As evidenced by well established overseas examples, such as those listed under Question 12, institutes offering dedicated collaborative and office spaces and are necessary infrastructure for transformative research in the mathematical sciences.

In recent years there has been an increased awareness in Australia of the importance of mathematical sciences to our economy. A previous report from the Chief Scientist identified that lag in mathematical research is detrimental to the country's prosperity, and Australian researchers must be internationally engaged and have strong international networks.

While major research and educational programs in mathematics and related disciplines have recently been funded, a gap for an internationally prominent residential mathematical research institute with sustained funding still remains.

In its 25th year of economic growth[i], Australia faces new challenges as the mining investment boom winds down. The Australian Government needs to look towards new and emerging areas of innovation across all sectors and fields to ensure we remain competitive in an economy that is increasingly lacking in momentum. New and long-term growth areas need to be developed and nurtured now to secure Australia's economic prosperity.

Australia needs to build its capability in the mathematical sciences arena. The continued evolution of the 'digital age' on the international stage, our students need to be made competent in analytical, statistical and computational skills and stay on top of international developments in this area. Produced by the Department of Employment, the *Employment Outlook to November 2020*[ii] report cites Scientific and Technical Services as the second largest area where employment is projected to increase by 151,200 (or 14.8 per cent) (to 2020).

For MATRIX to be internationally competitive research infrastructure, and build long term relationships with industry, a modern, dedicated building with sufficient capacity and increased operational funding needs to be guaranteed over a longer term. A dedicated incubator space will be made available within the building to support collaborations that will ideally lead to the start-up of potential new business ventures and/or with industry.

The long-term aim of MATRIX is to organise a variety of research programs, from one-week workshops to larger programs that could last several weeks.
Emphasis will be placed on creating ample free time for research collaboration. Longer programs contain embedded short conferences or lecture series.

MATRIX has already run four successful programs: *Higher structures in geometry and physics; Locally disconnected groups; Approximation and optimisation* and *C*-algebraic invariants for dynamics.* An program on *Topological recursion and quantum invariants* will be held in December.

The benefits of MATRIX to STEM in Australia include:

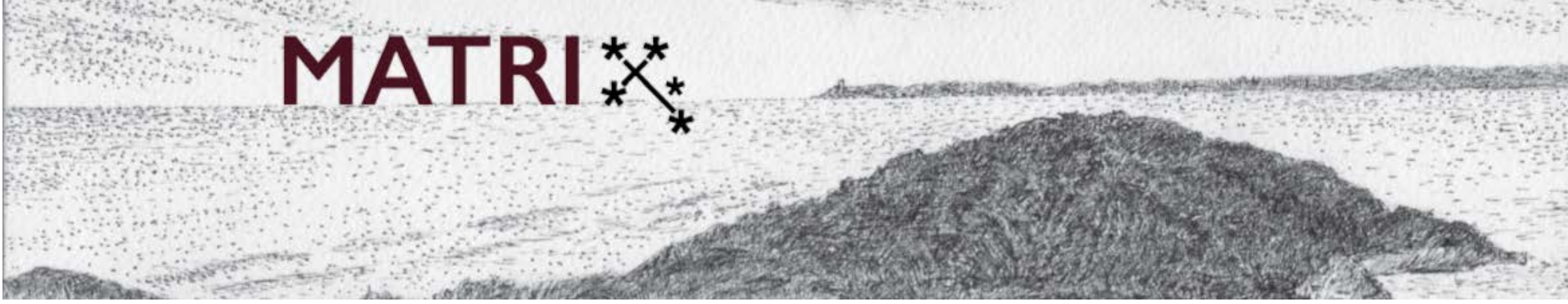
i. A vibrant, **dedicated** location for research and collaboration in the mathematical sciences;
ii. Enhance Australia's international reputation as a leader in mathematical sciences worldwide;
iii. The opportunity to engage more closely and regularly with top international researchers;
iv. The opportunity to explore industry collaborations;
v. Increase opportunities for women and students, especially from disadvantaged backgrounds.
vi. A concrete contribution to the national and state science and innovation policies;
vii. A magnet to attract outstanding young mathematicians with Australian ties for extended periods;

The MATRIX programs have already attracted participants from world-class institutes such as Nanchang Institute of Technology, Nanchang, Jiangxi Province (China); Massachusetts Institute of Technology (USA) and the École Polytechnique Fédérale de Lausanne (Switzerland).

It is important for Australia to liaise and collaborate with overseas residential mathematical research institutes such as listed under Question 12 to set coordinated research agendas. Such a network already exists in Europe and MATRIX believes this is an emerging trend in the mathematical sciences as they are inherently international.

We would like to see a research active mathematician included in the Expert Working Group and in the group of Capability Experts.

[i] Commonwealth of Australia, National Innovation and Science Agenda Report (2016), viewed 7th September 2016. http://www.innovation.gov.au/page/national-innovation-and-science-agenda-report
[ii] Labour Market Research and Analysis Branch (2016, pg 4), *Employment Outlook to November 2020,* The Department of Employment.



MATRIX Mathematical Research Institute

Research in the mathematical sciences flourishes with face-to-face interactions between groups of mathematicians. Intensive research programs at specialised mathematical research institutes provide an ideal environment for these interactions to take place, new collaborations to be created and advances to be made on important mathematical challenges. Transformative ideas and discoveries often arise unexpectedly. There are many examples where these discoveries eventually play an essential role in industrial applications and technologies that are now indispensable, such as the internet, online banking, Wi-Fi and GPS.

International examples

Almost every industrialised country has one or more mathematical research institutes. Well known examples include the Mathematical Sciences Research Institute (MSRI) in Berkeley, The Simons Center for Geometry and Physics in Stony Brook, the Banff International Research Station in Canada, Oberwolfach and the Hausdorff Institute in Germany, L'Institut Henri Poincare in France, Mittag-Leffler in Sweden, the Lorentz Center in Leiden, Bedlewo in Poland and Brazil's National Institute of Pure and Applied Mathematics (IMPA). The Isaac Newton Institute for Mathematical Sciences in Cambridge[1], established in 1992, is a successful gold-standard mathematical research institute. A key criterion for scientific programmes at this institute is the extent to which they are interdisciplinary, bringing together research workers with very different backgrounds and expertise. 26 Fields Medallists, 8 Nobel Prize winners, 23 Wolf Prize winners and 10 Abel Prize winners have attended.

In recent years there has been an increased awareness in Australia of the importance of mathematical sciences to our economy[2]. A lag in mathematical research is detrimental to the country's prosperity, and Australian researchers must be internationally engaged and have strong international networks.

While major research and educational programs in mathematics and related disciplines have recently been funded, a gap for an internationally prominent residential mathematical research institute with sustained funding still remains.

Related activities in Australia

The Australian Mathematical Sciences Institute (AMSI), as well as the Australian Mathematical Society, supports a distributed program of workshops around the country, but there is no single venue or location that has become identified as ***the place*** in Australia where collaboration in the mathematical sciences is fostered and supported through themed programs. AMSI's activities will interact with, and benefit from, the themed programs at MATRIX; for example through sponsorship of embedded workshops by making grants available to key participants, early career researchers and students.

Proposed Program

Launched in May 2016, MATRIX is Australia's first international research institute for the mathematical sciences established through a joint partnership between the University of Melbourne and Monash University; with seed funding from the ARC Centre of Excellence for Mathematical and Statistical Frontiers (ACEMS). MATRIX provides intensive residential mathematical programs at the MATRIX

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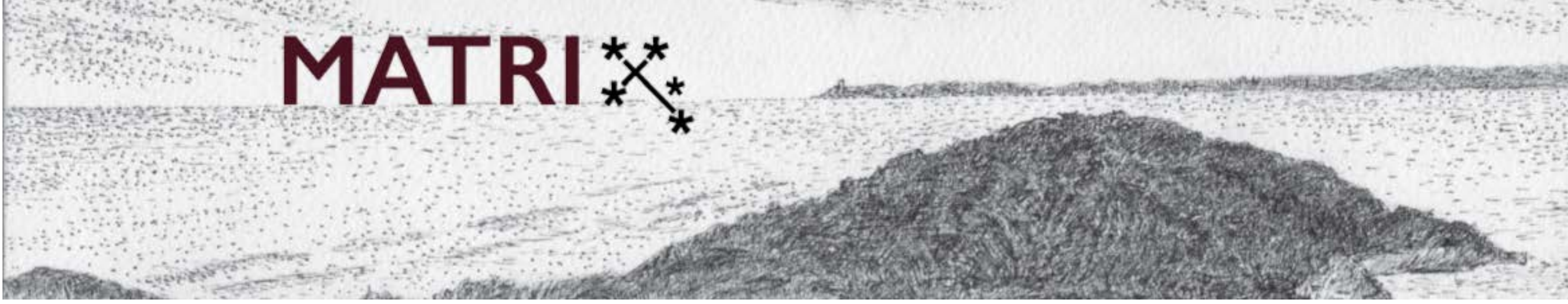
[1] The Isaac Newton Institute in Cambridge is the prototypical example of such an institute; https://www.newton.ac.uk

[2] http://www.chiefscientist.gov.au/wp-content/uploads/Importance-of-Science-to-the-Economy.pdf



House, a residential location in Creswick, Victoria. For MATRIX to be internationally competitive, and build long term relationships with industry, funding needs to be increased and guaranteed over a longer term.

The long-term aim of MATRIX is to organise a variety of research programs, from one-week workshops to larger programs that could last several weeks. Emphasis will be placed on creating ample free time for research collaboration. Longer programs contain embedded short conferences or lecture series.

MATRIX has already run four successful programs: *Higher structures in geometry and physics; Locally disconnected groups; Approximation and optimisation* and *C*-algebraic invariants for dynamics.* An program on *Topological recursion and quantum invariants* will be held in December.

Benefits

The benefits of MATRIX to STEM in Australia include:

i. A vibrant, **dedicated** location for research and collaboration in the mathematical sciences;
ii. Enhance Australia's international reputation as a leader in mathematical sciences worldwide;
iii. The opportunity to engage more closely and regularly with top international researchers;
iv. The opportunity to explore industry collaborations;
v. Increase opportunities for women and students, especially from disadvantaged backgrounds.
vi. A concrete contribution to the national and state science and innovation policies;
vii. A magnet to attract outstanding young mathematicians with Australian ties for extended periods;

Leadership

The Director of MATRIX is Professor Jan De Gier, who is also Deputy Director of the ARC Centre of Excellence for Mathematical and Statistical Frontiers (ACEMS), University of Melbourne. The Deputy Director, Professor David Wood, is an ARC Future Fellow within the Discrete Mathematics Research Group, Monash University. MATRIX employs a full-time Executive Officer who is responsible for the management of MATRIX's resources and staff and the provision of executive support to the Director and Deputy Director; including support to the MATRIX Advisory Board and Scientific Committee.

MATRIX is currently operating on a small operational budget for five years with office infrastructure for twenty people on the Creswick campus of The University of Melbourne. MATRIX aspires to be one of the gold-standard research institutes around the world, such as MSRI in Berkeley or the Newton Institute in Cambridge, with sustained funding.

Australian Government
Office of the Chief Scientist

Australian Academy of Science

THE IMPORTANCE OF ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES TO THE AUSTRALIAN ECONOMY

MARCH 2015

Prepared by the Centre for International Economics for the Office of the Chief Scientist and the Australian Academy of Science.

8. THE SOURCE OF ADVANCED PHYSICAL AND MATHEMATICAL SCIENTIFIC KNOWLEDGE

Chapter 6 explains that output produced using inputs that embody useful knowledge from the APM sciences makes up 11.2% of the Australian economy. This is the direct impact of those sciences.

This chapter discusses the ways in which the individual disciplines within the APM sciences contribute to that impact.

BREAKING DOWN THE SCIENCE-BASED SECTOR

As described in Chapter 2, there are three sources of useful knowledge within the APM sciences:

- the core disciplines (physics, chemistry and mathematics)
- the non-core disciplines (such as the earth sciences, which are based on a combination of principles from the core sciences)
- the direct combination of principles from core and non-core disciplines.

ACTIVITY BASED ON A SINGLE CORE SCIENCE DISCIPLINE

Of the 158 science-based industry classes in the ANZSIC classification system, 60 use inputs that embody useful knowledge from a single core discipline.

For those 60 industry classes, total GVA was $246 billion in 2012–13. The results of the workshop and industry consultations suggest that 19.0% of this GVA was based on the APM sciences. This means that the size of the sector based on a single core discipline was $47 billion (19.0% of $246 billion). This is 3.6% of the GVA of the economy as a whole.

Within the sector based on a single core science discipline, the most important industry classes are those in the finance, computing and transport industries based on mathematical sciences and those in the pharmaceuticals and plastics industries based on chemistry (Table 8.1).

ACTIVITY BASED ON COMBINATIONS OF THE CORE DISCIPLINES

Of the 158 science-based industry classes, eight are based only on the earth sciences and 90 are based on a combination of other APM sciences.

The earth sciences

For the eight industry classes based on the earth sciences only, total GVA was $19 billion in 2012–13. The results of the workshop and industry consultations suggest that 22.3% of this activity was produced from inputs that embody useful knowledge from the earth sciences. This means that the size of the sector based on earth sciences was $4.2 billion in 2012–13 (22.3% of $19 billion), or 0.3% of the economy as a whole.

The two key industry classes based on earth sciences outputs were:

- *mineral exploration*, which produced $2.5 billion of output from inputs that embody useful knowledge from the earth sciences in 2012–13
- *other heavy and civil engineering construction*, which produced $1.5 billion of output from such inputs in 2012–13.

Table 8.1 Sector based on a single core science discipline

Industry		Single core science discipline	Science-based GVA ($ billion)
6221	Banking	Maths	5
7000	Computer System Design and Related Services	Maths	5
4610	Road Freight Transport	Maths	4
1841	Human Pharmaceutical and Medicinal Product Manufacturing	Chemistry	2
6240	Financial Asset Investing	Maths	2
6330	Superannuation Funds	Maths	2
1912	Rigid and Semi-Rigid Polymer Product Manufacturing	Chemistry	2
All other industry classes based on a single core science discipline			25
Total			47
Total (share of total GVA)			3.6%

Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings industry*, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Source: The CIE.

Output based on combinations of multiple disciplines

For the 90 industry classes based on combinations of principles from multiple disciplines, total GVA was $276 billion in 2012–13. The results of the workshop and industry consultations suggest that 34% of this activity was produced from inputs that embody useful knowledge translated from the APM sciences. This means that the size of the sector based on some combination of the APM scientific disciplines was $94 billion in 2012–13 (34% of $276 billion), or 7.3% of the economy as a whole.

Within the sector based on multiple APM scientific disciplines, the key industry classes are in mining (including *oil and gas extraction*, *iron ore mining* and *gold mining)*, financial services (including *general insurance*) and communications (Table 8.2).

Table 8.2 Sector based on multiple APM sciences disciplines

Industry class		APM scientific disciplines	Science-based GVA ($ billion)
700	Oil and Gas Extraction	Maths, physics, chemistry and earth sciences	16
6322	General Insurance	Maths, earth sciences	8
801	Iron Ore Mining	Maths, earth sciences	7
804	Gold Ore Mining	Maths, earth sciences	7
5801	Wired Telecommunications Network Operation	Maths, physics	7
8520	Pathology and Diagnostic Imaging Services	Maths, physics and chemistry	5
5802	Other Telecommunications Network Operation	Maths, physics	4
600	Coal Mining	Maths, physics, chemistry and earth sciences	4
All other industry classes based on combinations of disciplines			37
Total			94
Total (share of total GVA)			7.3%

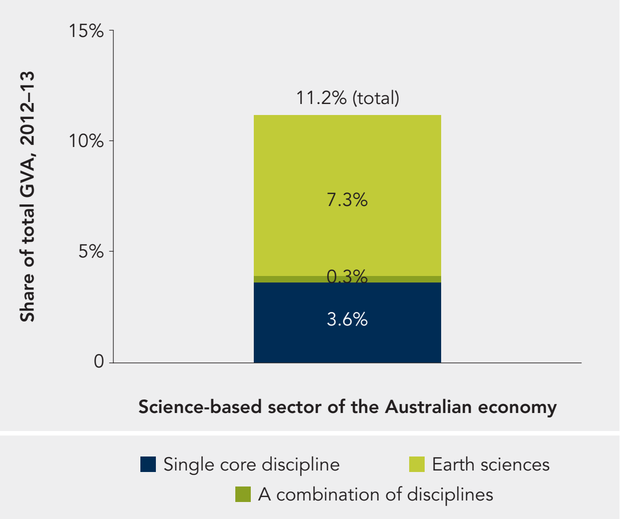
Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Source: The CIE.

THE COMBINED RESULT

The results outlined above are summarised in Figure 8.1, which shows where the useful knowledge that directly underpins 11.2% of Australian economic activity comes from. Most of it comes from knowledge that is created by combining disciplines.

Figure 8.1 The sector based on the APM sciences, by source of useful knowledge (% of total GVA)



Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Data source: The CIE.

CASE STUDY 8: WI-FI

This case study demonstrates multidisciplinary science's impact on productivity. It shows how physics and mathematics were combined to produce what is now a ubiquitous technology used by millions of businesses and households.[17]

The technology that became Wi-Fi was invented by Australian scientists working at the CSIRO's radio astronomy unit in the late 1980s and early 1990s. They needed to send large amounts of data between telescopes and their computers. They decided to send these data using radio waves (that is, wirelessly).

To send data using radio waves, they had to manage radio interference created by different sources (a physics problem). To do this, they created a complicated mathematical algorithm; that is, they solved the physics problem with mathematics.

The scientists realised that their wireless technology could have many other applications. They converted it to a small printed circuit that could be installed in personal computers. That step required specialist advanced electronic engineering—a capability that existed at CSIRO at that time. This incarnation of the technology became the basis of Wi-Fi technology used widely today.

17 Sources for this case study: Hans Bachor (ANU), Colley (2012) and CIE.