Institution: Cambridge University

Unit of Assessment: B10

a. Context

The Departments of Applied Mathematics and Theoretical Physics (DAMTP) and Pure Mathematics and Mathematical Statistics (DPMMS) that comprise this UoA cover a very wide range of mathematics. Consequently both the application areas and impact types are broad, requiring flexible and varied approaches to ensuring that impact arises from our research.

While we have key strengths in areas which have clear direct application, for example in fluid dynamics, numerical analysis, stochastic analysis, probabilistic modelling and number theory, we also have depth in areas such as theoretical particle physics, quantum theory, relativity, cosmology, astrophysics and algebraic geometry, which at first glance might seem less obvious precursors for impact.

Unsurprisingly, the beneficiaries of our research are diverse: industry; professional services, policy makers; students in secondary and tertiary education; and society at large. For these user groups, the range of our impacts includes economic impacts (from research in areas such as fluid mechanics and numerical analysis), impacts on public policy (from research in risk communication and fluid flow) and impacts on society (from astrophysics, cosmology and theoretical physics more broadly).

b. Approach to impact

The UoA makes use of structured mechanisms to support impact, some provided by the University, some from within the UoA itself, as described below. However, these are enablers not prescriptions. The University as a whole and the UoA in particular, recognise that significant flexibility is needed to optimise our impact. There is strong support for technology transfer, industrial engagement, and both public engagement and education, but there is also a recognition that industrial and economic impact can be achieved in different ways, and that the optimum strategy depends on the nature of the research, requirements of funders, potential beneficiaries, and the motivation of researchers. Moreover, the breadth of our types and potential types of impact requires us to be open to exploring new mechanisms to support impact.

Collaboration with Other Disciplines

Mathematics is distinct amongst the disciplines for its underpinning of engineering, physical, biological, medical and social sciences. Therefore a large part of our impact is through, or with, these other disciplines. Much of our research has strong interdisciplinary elements; our approach is to encourage research which is collaboratively interactive rather than merely "collaboratively linear" so that we can play our full part in contributing to impact. For example, within the University, our researchers engage with programmes such as the Cambridge Centre for Climate Science, the Cambridge Forum for Sustainability and the Environment, the Energy Efficient Cities Initiative, and Energy@Cambridge.

Problem-Oriented Research

Much of our research is problem-driven so that, in addition to developing new mathematics, practical solutions to industrial and societal problems are found. As shown by the case studies, these span engineering, innovative physics, information theory and cryptography. Here the path to impact may be part of a longer-term engagement with beneficiaries (who may also be funders) giving rise to cycles of new challenging research problems and solutions.

Supporting Staff to Create Impact

Staff contribution to impact is supported by our mentoring system and a UoA-wide commitment to continuing and expanding the impact of our research to the public, education, industry and policy makers. Staff are also encouraged to teach in international summer schools, to interact with the media, and to engage with the general public and schools; our facilities are used to make educational films based on our research. The School of Physical Sciences, within which the UoA sits has four knowledge transfer facilitators in post and a further one through the Turing gateway (see later).

Staff in the UoA are incentivised to maximise the impact of their research through freedom to choose their lines of work that enables them to pursue impact activities and by recognition of their

impact activity, such as having spun out a business or being a member of a senior external advisory panel, in promotion. The University has a generous IP policy providing a reasonable share to the individual and there is no limit set by the University to the external earnings so long as their University duties are met. Further, there is flexibility in the use of sabbatical leave to pursue impact-related matters.

Programmatic activities that promote impact.

(i) *The Millennium Mathematics Project*

MMP, established in 1999, is a mathematics education and outreach initiative for ages 3 to 19 and the general public. The MMP is a collaboration between the Faculties of Mathematics and Education at the University of Cambridge, and is active nationally and internationally. Its focus is on increasing mathematical understanding, confidence and enjoyment, enriching everyone's experience of mathematics, and promoting creative and imaginative approaches to teaching and learning maths. The project consists of a family of complementary programmes, including the very successful NRICH website, online mathematics magazine Plus, and face-to-face work with schools and the public. All this provides a unique medium to communicate UoA research to a broader audience. The MMP's online outreach and education resources currently attract over 6 million visits and more than 25 million page views a year in total, and around 5,000 teachers and 25,000 school students are engaged annually with face-to-face activities, including teacher training and professional development activities. The MMP was also a partner project in the London 2012 Olympic education programme. It received the LOCOG Inspiremark to produce resources for schools and the public which explored the applications of mathematics within sport and Olympic and Paralympic planning and infrastructure in the lead-up to the 2012 Olympic and Paralympic Games; these resources attracted over 1.5 million page views in the lead-up to 2012. Barrow wrote daily columns for the Daily Telegraph on mathematics and sport throughout the 2012 Olympics and lectured widely, while Hawking introduced the Paralympic Opening ceremony to a world-wide television audience. The MMP has a growing social media presence, with more than 25,000 followers in total on Twitter and Facebook. In addition, the Cambridge Mathematics Education Project is a major initiative for advising government on mathematics education and producing materials for schools.

(ii) *Winton programme for the public understanding of risk*

This programme, endowed by Winton Capital Management, funds Spiegelhalter and support staff in public engagement activities, often in collaboration with external partners. Details are provided in the impact case studies, but highlights include frequent appearances on radio and in printed media commenting on risk and statistics stories in the news, fronting a TV documentary on chance and risk, producing a popular science book, presentations at science festivals and other public fora, and collaborations with agencies concerned with risk assessment and communication. An 'agile' approach is needed to respond to breaking stories: for example when child heart surgery was stopped at Leeds General Infirmary, Spiegelhalter immediately joined the team rapidly reanalysing the data and enabling it to reopen, and when a story about '13000 needless deaths' featured in the Sunday Telegraph in July 2013, he was commissioned to write a rapid opinion piece in the British Medical Journal repudiating this claim.

(iii) *BP Institute* (BPI)

The BPI was founded in 1999 through an initial endowment of £22M to support 5 academic posts, one of which is at professorial level. DAMTP is one of 6 university departments who are members of BPI and currently has two staff holding joint appointments (Caulfield, Neufeld). The Institute has developed an international reputation for its research in multiphase flow and, while BP continues to offer the Institute staff interesting problems and data, the Institute's intellectual independence is contractually guaranteed, enabling it to concentrate on research that fits its academic interests and capabilities. BP have a senior employee who regularly works from the site, with a boundary-spanning role acting as a technological gatekeeper, and with a clear understanding of the problems faced by BP and the individual skills of the researchers in Cambridge. Through courses, seminars and visits to BP's offices, BPI researchers meet up to 100 BP staff each year, leading to very effective formation of knowledge-led networks. In 2010 BP added a further £3.9M to the BPI endowment, a testament to the value it places on this initiative. The BP Institute's work has led to a spin-out company and to several joint patents.

(iv) *G. K. Batchelor Laboratory* (GKBL)

This facility, established by Professor George Batchelor in 1964, has played a significant role in the impact of DAMTP, UK and international research in fluid mechanics for the past 50 years. It is a major component of the UoA's biennial Open Days, which in the period since 2008, have hosted over 2500 visitors. The laboratory provides a direct visual experience of fluid flows that contribute to the public understanding of science. Some of our laboratory facilities have attracted users from outside of academic research. For example, our Temperature Controlled Laboratory (-40°C to +30°C) was used for six weeks for filming parts of the BBC Frozen Planet series, three members of our academic staff and four lab technicians were used in an advisory role while the BBC were filming in the lab. Experimental research in fluid mechanics, supported by a range of industrial sponsors including British Gas, Arup and Laing O'Rourke (natural ventilation) and AWE (mixing), has led directly to impact. Research leading to impact has also been carried out in the GKBL for companies such as Schlumberger, Yorkshire Water and BP.

(v) *Isaac Newton Institute for Mathematical Sciences* (INI)

Following an initiative by Cambridge mathematicians, supported by the University (including the University's HEIF5 allocation) and with significant investment in buildings by Cambridge colleges, the INI was established in 1992 with primary objectives: to organise research programmes of the highest quality across the entire range of mathematical sciences; to attract to the best scientists internationally; to ensure that 80% of the programmes are interdisciplinary. The INI, which continues to receive significant support from the University, attracts over 1500 scientists per year; overseas visitors are encouraged to visit universities across the UK, and around 500 seminars are added annually to its web archive of streaming video. The Institute has an extremely high international reputation for the breadth and quality of its programmes. It is proactive in encouraging submissions in fields of strategic importance and of relevance to all Research Councils. It is a unique resource for the UK, which can make a vital contribution to helping the Research Councils achieve the key goal of a strong research base, engaged in cross-disciplinary collaboration. The INI also brings academic researchers in the mathematical sciences together with industrial, commercial and government organisations and individuals through activities such as the Open for Business events. See also the Turing Gateway to Mathematics below.

Strategic Initiatives/Networks/Enablers

(i) *Cambridge Enterprise* (CE)

Cambridge Enterprise is a wholly owned subsidiary of the University of Cambridge which is responsible for commercialisation of the outputs of research within the University. It makes arrangements for licensing of inventions under a scheme where the inventor or inventors, the Department and the University share income. It also provides administrative support for University staff (and students) undertaking consultancy work. About 6 members of the UoA have made or are making use of Cambridge Enterprise in arranging consultancy or commercialisation.

A technology investment company with funds of £50M, known as Cambridge Innovation Capital, has been established by the University and other investors. This will provide follow-on investments in new ventures in the Cambridge area, complementing the healthy Angel and seed funding, Cambridge Enterprise the Seed Enterprise Investment Scheme (SEIS) fund already present in the Cambridge environment.

(ii) *Cambridge Centre for Climate Science* (CCfCS)

DAMTP is a founding member of the CCfCS, an interdisciplinary centre across 5 University Departments and British Antarctic Survey aimed at elucidating and explaining the underlying science that controls the climate. The centre has strong links with the UK Meteorological Office and provides a forum for input of climate science into policy through the Cambridge Centre for Science and Policy (CSaP).

(iii) *Cambridge Forum for Sustainability and the Environment* (CFSE)

DAMTP hosts the CFSE which is led by Linden as Director. The CFSE is an interdisciplinary group of senior academics from 17 departments across the University whose role is to articulate the research agenda in the areas of sustainability and the environment, to provide an internal forum for discussion and opportunities for communication with external organisations and individuals working in this area. It has representatives from CSaP and the Cambridge Programme for Sustainability Leadership (CPSL) to provide access to policy makers and industry.

(iv) *Cambridge Centre for Science and Policy* (CSaP)

CSaP is hosted by the University to broaden its engagement with policy makers. Kelly was part of the initial steering group, and remains on the Executive Committee. Indeed Kelly was a key contributor to the decision that transformed the mission of CSaP from one of carrying on research related to public policy to that of being a vehicle to link researchers across the University (and beyond) to policy makers. He is also on the Steering Committee for Cambridge Public Policy, whose Masters in Public Policy is a one-year practice-oriented programme. In the period 2011-2013, members of the UoA have met with 65 CSaP policy fellows from UK government departments, 11 from the EU, 7 from industry and 3 others (a total over two years of 91); on average meetings with Spiegelhalter have been given the highest rating by CSaP fellows.

[text removed for publication]

Economic Impacts by facilitating knowledge transfer to industry and creation of new businesses

The facilitation of knowledge transfer to industry has been mentioned in the context of the BP Institute. Additionally, staff (Cowley, Hinch, Peake) take part in annual industrial 'sandpits', such as the European Study Group with Industry, in which industry members present research problems. DAMTP has a close association with the Smith Institute for Industrial Mathematics and Systems Engineering who are national leaders in the provision of mathematical consultancy for business, industry and government. DAMTP was a founding partner of the Institute, and is currently represented through Peake (member of the Institute Council), and Cowley (member of the Scientific Committee). Institute activities in DAMTP include: industrial seminars (around 2 per term over the last three years); an industrial mathematics study group for PhD students, run by Institute staff; opportunities for research student internships and CASE awards, approximately one a year; and consultancy activities involving academic staff.

Beneficiaries

General public

The impact of our research is communicated to the public through a variety of avenues. For example, as described above, the Millennium Mathematics Project (MMP) is a mathematics education and outreach initiative for ages 3 to 19 and the general public. The MMP's various programmes have won many awards and our resources have been repeatedly commended by the UK Government's Department for Education. In 2006 the Queen presented the project with the Queen's Anniversary Prize for Higher and Further Education, honouring 'outstanding achievement and excellence' at world-class level.

Mathematics and statistics are of major interest to the public, in particular their importance in judging evidence about issues being publicly debated. The Departments also maintain a high media profile, particularly through the contributions of Hawking and Spiegelhalter. Wadhams plays a major role in polar oceanography and has made frequent media appearances explaining the effects of climate change on polar sea ice.

Through the MMP and the Winton programme there has been increasing engagement with the public and the media, both directly and through contributing to external initiatives by, for example, the Royal Statistical Society. As part of the annual Science Festival the UoA holds Open Days in which the research of the two departments is shown to the public. This features displays, guided explanatory tours, talks and hands-on activities explained by members of the staff within the different research groups. Attendance at the biennial Open Days have been increasing and there were around 1000 visitors at the Open Day in March 2013.

School Education

The UoA has an increasing focus on improving mathematics education in schools. This is a major component of the MMP described above, the Cambridge Mathematics Education Project (CMEP) is a major joint DAMTP/DPMMS initiative funded by the UK Department of Education to develop novel challenging A-level materials. In addition we act as curriculum advisors to the Department of Education, and are advising on the development of a new post-GCSE non-A-level mathematics qualification. MMP also advises Cambridge University Press on the provision of mathematical materials for their international market with around 213,652 units distributed over the last four years. MMP is also a formal advisory partner of the Korean Government's Foundation for the

Advancement of Science and Creativity who have sent cohorts of teachers to take part in MMP programmes, 37 teachers to date have visited.

Industry

Much of the research in fluid mechanics, analysis, and probability and statistics is motivated by problems arising from industry. As described in the Impact Case studies, the UoA makes a significant contribution to economic prosperity through the application of mathematics to these problems. We also work with colleagues in other departments (engineering, plant sciences etc.) on industrially related problems. While the UoA does not offer institutional consultancy, members of the UoA act as consultants across and range of industrial and policy issues; e.g. Weber is a consultant to JLT Re (London) on Catastrophe Risk Management. Mathematics provides training that underpins physical science and engineering and, increasingly, the biological sciences, around 30% of our students pursue a career in industry. The knowledge and skills obtained by students, postdocs and staff are important for industry and for the financial sector. Although this connection is not fully captured by the case studies it provides an underlying connection with industry (e.g. Microsoft, Schlumberger, Xaar). The underlying skill is the ability to apply analytical thinking to solve problems across a wide spectrum, and we are increasingly providing training in awareness of issues such as IP and management.

Policy makers

Through the Winton programme there have been major contributions to public debate and policy on plain packaging of cigarettes, revised cancer screening leaflets, the hazards of PIP breast implants, methods for hospital mortality monitoring, and so on (Spiegelhalter). Work carried out on the fundamental physics of storing CO2 underground has led to significant policy changes in Australia and a reconsideration of the basic issues in the EU (Huppert, Neufeld). Kelly was Chief Scientific Adviser at the Department for Transport for three years (half time) from August 2003, using his extensive research into networks. He has continued to play an active advisory role during this REF period and was also part of the Council of Advisors on Science and Technology in July 2013. Baumann and Davis were involved in US Science Policy White Papers on aspects of Theoretical Cosmology. The UoA also works with the Cambridge Centre for Science and Policy (CSaP) (see above).

c. Strategy and plans

The UoA's strategy is to continue to maximise the impact of its research by using a flexible approach drawing where appropriate on the approaches to impact discussed above. This includes continuing to provide opportunities for staff to devote some of their time to impact activities and to recognise this as a legitimate part of their workload and contribution. The UoA also has two major strategic initiatives to increase the impact of its research: the Turing Gateway project which began in 2013, and the Millennium Mathematics Project which is described above and will continue over the next period.

Public engagement

In the public arena we will continue and strengthen our activities around public Open Days and the Millennium Mathematics Project, and provide support and opportunities for staff to work with the media. We will continue to train our staff and research students to provide accessible accounts of their research during Open Days. The Winton programme will continue to engage with the media and directly with the public, in particular through collaboration in producing interactive websites to explain, for example, cardiovascular risk. We will continue our annual technical conferences organised by the relativity and cosmology group which have a major public outreach day (in September 2013 the speakers were Liddle, Cox and Hawking and in 2011 were Thorne, Perlmutter and Rees).

Industry and business

The Turing Gateway to Mathematics (TGM) is a joint initiative of INI and the UoA with a remit to facilitate knowledge transfer from the mathematical sciences into other disciplines and applications. The University supported this initiative by funding a Knowledge Transfer Facilitator. TGM activities to date have included industrial statistics, planning and policy-making challenges for local government, stochastic and statistical models for industry, mathematics of liquid crystals, financial risk management and energy systems. Activities over the next few months include optimization for space engineering, overlapping intervals in finance, mathematical techniques in animal modelling, and a Centre for Mathematical Science Showcase event. Other projects are also

in progress covering areas such as Big Data in Space, mathematics in middleware (sensing), support for EPSRCs Energy & Digital Economy activity, statistics in journalism, and a national biology in maths study group. There are numerous opportunities for cross-fertilization between the INI and the TGM. The optimization for space engineering, with the European Space Agency, arose from an INI programme on Polynomial Optimization programme workshop and funding is being sought from the MRC to support a programme of work arising out of the recent INI programme on Infectious Disease Dynamics.

The UoA has recently created a facilitator post to promote interaction with industry and business through Cambridge Enterprise (CE). The UoA will also benefit from the overall University's £3.9M EPSRC Impact Acceleration award, e.g. Coordinator, who has recently been appointed.

We plan to continue and expand our industrial impacts by working with current and new sponsors of research. These include BP on CCS, Arup and Laing O'Rourke on natural ventilation, and the Meteorological Office on improving models for weather and climate prediction. For example, we have been awarded an iCASE with BP to study hydraulic fracturing. Mathematical analysis underpins much of the modelling and interpretation of climate change and we foresee increasing roles of the UoA in these arenas building on links associated with case studies on atmospheric modelling and statistical interpretation of data. The UoA was recently awarded a £2.3M EPSRC Programme Grant on the Mathematical Underpinnings of Stratified Turbulence, which has provision for workshops with industry with interests in mixing processes. This work is also expected to have impact on parameterisations in climate models.

Research knowledge transfer to industry via education

The UoA is committed to continuing to produce graduates with high analytical skills and expertise in a wide range of mathematics and with knowledge based on cutting-edge research, which will enable them to enhance the capabilities of industry and business in the UK and abroad.

Centres for Doctoral Training (CDTs) provide a particularly important opportunity for active engagement between PhD training and industry and business. Cambridge Mathematics has one CDT, the Cambridge Centre for Analysis (CCA), which is running very successfully, will continue to operate until 2017 and which has provided opportunities for interaction with companies such as Microsoft, Schlumberger and EADS. We are planning to continue and extend the CCA by including applications of analysis and the mathematics of information, which should open up new connections to industry and business. We are seeking to exploit relations already built and resources offered to seek further funding opportunities. Plans are also underway for a programme in the Fundamental Fluid Mechanics for Industry jointly with the Departments of Engineering, Chemistry, Chemical Engineering and Biotechnology and the BP Institute. We have some industrial partners and are seeking further resources from other industrial users. This arose from a perceived need from UK industry for researchers trained in the three basic modes of fluid dynamics research: theory, experiment and computation. The UoA also currently has a number of EPSRC iCASE awards and these will also be enhanced through the above programmes.

d. Relationship to case studies

The different Case Studies show the variety of development routes that have been taken. For example, problem-oriented research led to the impact case studies on ink jet printing, dissolved air flotation, and the design of low-energy buildings. The Winton programme led to the case study on the public communication of risk and uncertainty. `Image processing for fluid dynamics' relied heavily on the UoA's support for staff (in commercialising the research), as did the case study on Stephen Hawking (who was given significant time for his public engagement work). As a final example, our connections in school education enabled a significant part of the impact created by Sun|trek.

Not all of our impact could be expressed in case studies. In particular, one example of multi-billion dollar impact arising from the agile application of our fundamental research was too sensitive for the beneficiary to permit it to be published at all.