Institution: University of Oxford

Unit of Assessment: 10 – Mathematical Sciences

a. Context

The Mathematical Sciences at the University of Oxford have a long history of proactive engagement with users from outside academia. The industrial engagement mechanisms that we pioneered in the 1960s have been adopted globally. Today, the diverse community of researchers from the Mathematical Institute (Oxford's Department of Mathematics) and the Department of Statistics is supported by departmental and institutional structures that enable researchers to realise the impact of their work in many arenas.

Research from right across our portfolio has impact outside academia. The main beneficiaries are companies, Government agencies, policymakers, and the general public. We enhance and support company research across a wide variety of sectors, explaining processes and helping to reduce costs; we enable the development of new products, processes and algorithms; we advise on new public policies; and we increase public understanding of, and engagement with, the mathematical sciences.

Our extensive impact activities span the UoA and are based on a diverse set of engagements. Over the REF period, we have engaged with over 143 companies and had research projects with 56. These range from individual student projects to multiple projects at formal centres. Three classified case studies explain how our work underpins National Security. Public engagement activities have included everything from small scale events for local schools to the high profile media appearances of du Sautoy, which attract millions of viewers.

Achieving impact is underpinned by substantial investment, ranging from the recent appointment of a Director of External Relations and Public Engagement for Mathematical Sciences to the University's establishment, in 2011, of an Innovation and Impact Team for the Sciences. Above all it depends on a culture in which impact is recognised and rewarded.

All data cited here refer to this REF period unless otherwise stated.

b. Approach to impact

Our approach is based on the belief that interactions outside academia enrich the Mathematical Sciences, bringing challenging new problems and ideas. Three principles underpin our strategy:

- active engagement with end users leads to academic interest and impact;
- impact usually follows from well-nurtured relationships;
- achieving impact requires appropriate institutional support and infrastructure.

Recognising the rapidly evolving needs of the external environment, we constantly monitor and evaluate our activities. Our structures are enabling, not confining, and encourage serendipitous interactions alongside more formal projects.

How we interact, engage and develop relationships with key users and beneficiaries
(a) Initial contact with new users. Initial contacts arise in many different ways: personal or website contact; referral from colleagues in other disciplines; existing relationships within the external organisation; as part of an individual, departmental or institutional proactive approach (e.g. through the Systems Approaches to Biomedical Science Industrial Doctorate Centre (SABS-IDC) or the University Innovation and Impact Team, both described below); via an external agency such as the Knowledge Transfer Network in Industrial Mathematics (KTN) or a Study Group with Industry (see later). Right from the start, we identify an academic point of contact who ensures that individuals with relevant expertise from across the mathematical sciences are brought into play.

Initial contact is followed by scoping meetings, at which areas of common interest and strategies for progress are identified. Such strategies will depend on the exact nature of the project, but during the period have included:

- Presentation of a specific problem at our Industrial and Interdisciplinary Workshop series (43

industry problems from 20 companies and two hospitals);
- Sponsorship of research projects on the MSc in Mathematical Modelling and Scientific Computing (29, from 11 companies) or undergraduate summer projects (one in the period);
- Sponsorship of DPhil projects (12 new CASE awards, 10 SABS-IDC studentships, two partially funded, and three fully funded studentships secured, from 17 companies);
- Sponsorship of Postdoctoral Projects (6 fully funded projects secured, from 5 companies);
- Consulting (54 consultancies undertaken).

Regular early contact with companies ensures that momentum is sustained.

(b) Engaging with users to develop impact from current or pre-existing research. We believe that the most effective way to develop impact is to ensure that Oxford researchers are able to interact directly with end users. Thus, students and PDRAs working on industrial projects spend time embedded in the partner company, which then benefits directly from the research while we stay abreast of developments. Reciprocal visits by industrial supervisors ensure that relevant current/pre-existing research, beyond that envisaged in the original project, is readily identified.

Our research has been exploited by 17 graduate students undertaking internships with 14 companies. These internships have enabled the students to work on short-term projects of direct benefit to their companies, as well as engaging supervisors and their industrial counterparts. For example, one student spent 10 weeks at Google, applying our research on image processing to the recovery of text from ancient scrolls. We have used funds from the EPSRC-funded Knowledge Transfer Secondments grant to enable one postdoctoral researcher to spend time at DuPont (see later). Oxford's part-time MSc in Mathematical Finance provides another direct route to impact. Through their dissertation work, 105 students who are practitioners in 24 financial institutions have brought Oxford's existing research to bear on problems arising at their place of work.

An important strand of our activities is public engagement. High profile work in this area involves du Sautoy, Charles Simonyi Professor of the Public Understanding of Science (who reaches huge audiences through his bestselling popular science books, TV and radio shows, Flash games and online courses) and Penrose (Emeritus Professor). This is complemented by smaller-scale activities such as annual schools lectures or Porter's schools programme, which introduces students age 13-16 to network science. We recently appointed Goriely as Director of External Relations and Public Engagement in order to dramatically extend our activities in these areas.

Our staff are active in public policy debates and take up advisory roles for governments, ensuring that our research and expertise informs public decision making.

(c) Developing and deepening relationships with key partners. Long-term relationships bring increased value to both sides: academics develop familiarity with the needs of collaborators, who, in turn, appreciate the value of the contribution that academics can make. The mechanisms used to sustain and develop a relationship are necessarily bespoke. They might, for example, incorporate a series of CASE studentships, MSc projects or contracts. Some engagements occur through strategic company investments, for example, through the Nomura Centre for Quantitative Finance (£777k provided by Nomura) and through the interdisciplinary Oxford-Man Institute for Quantitative Finance (OMI; £15.5M investment by Man Group), in which the Mathematical Sciences play a pivotal role.

(d) Study Groups. Study Groups with Industry are a particularly effective mechanism for engaging companies with our research. They generate immediate and direct impact. Pioneered in Oxford in the 1960s, they involve a week-long brainstorming session on topical issues with an end-user representative. Oxford is heavily involved in international activity in this area. Through the Oxford Centre for Collaborative Applied Mathematics, we have financially supported the launching of Study Groups with Industry in eight countries. Study Group problems often pump-prime new collaborations with industry, leading to sustained impact.

Evidence of the nature of those relationships and interactions.
We provide exemplars of the many industrial relationships initiated and/or nurtured over the period.

1: HSBC. Our relationship with HSBC illustrates how significant collaborations can develop from

an initial personal contact. Initiated through an ex-student working in the City, it led to four CASE studentships (2003, 2005, 2009, 2011). Two students moved to HSBC after finishing and exploited their research for HSBC's benefit. In 2013, the commercial success of the work led HSBC senior management to fully fund two further studentships in complex systems approaches to financial risk and robust asset allocation. The relationship has expanded and is now led by four faculty.

2: Man Group. We were key partners in responding to the call from Man Group that resulted in the establishment of the multidisciplinary OMI in 2007. The current Director is Lyons, on secondment from Mathematics. 35% of the investment in the OMI has been spent on mathematical activities (including 15 students, 8 postdocs and research fellows, 20 visitors, and 19 workshops). Man Group has co-located its proprietary research activity with OMI's academics. Man cite the key benefits of working with Oxford as the close contact with cutting edge quantitative research not yet in the public domain, access to specialists, and first right of negotiation on commercially exploitable research. Impact is being realised in areas include trading models, trade execution, robust decision protocols for investment management, and automated market data cleansing tools for model validation.

3: BP. Whereas the creation of OMI was in response to a specific call, with BP we have deployed several mechanisms to build a strong relationship across its diverse business. Oxford's relationship with BP was launched in 2010 following a University-wide meeting with BP where high-level intent to collaborate was agreed. Breward led the development of our interaction. We visited three BP business units (Hull, Pangbourne, Sunbury) and identified opportunities to engage at the technical level. These visits have resulted in 6 workshops (both in Oxford and at BP), a summer studentship (lubricants), two CASE studentships (enhanced oil recovery; additives in lubricants), and a fully-funded studentship (seismic inversion). In addition, BP have funded a one-year PDRA post in Decision Analytics who works both in Oxford and at BP identifying areas for future collaboration.

4: Pharmaceutical Industry. The SABS-IDC, directed by Deane, provides a framework in which science faculty can engage efficiently and effectively with 14 companies from the pharmaceutical sector. In a departure from usual business processes, an Open Innovation agreement makes research from the SABS-IDC immediately available to all partners. This not only provides exceptional value for money for industrial partners, it also encourages inter-company interactions. For example, Roche and UCB Pharma have co-sponsored several projects and are now both using the same code for antibody drug development. UCB Pharma also funds a PDRA working in this area. The training programme is developed, refined and delivered in conjunction with industry, and all projects are industrially sponsored and co-supervised. Over the first three years 25 short projects and 10 DPhils with 7 different companies were undertaken in the mathematical sciences.

In addition, AWE, BetFair, DuPont, GlaxoSmithKline, InhibOx, Institute and Faculty of Actuaries, KBC Alternative Investment Management Ltd, Lloyds TSB, Mathworks, Microsoft, NAG, Nomura, NVIDIA, RAL, Schlumberger, SELEX, Thales, and Unilever have each provided at least £10k of funding for Mathematical Sciences research in the period.

Following through from these activities to identify resulting impacts

In order to maximise their benefit, all projects with industrial partners undergo regular review and iteration. Many of our relationships have been nurtured over a long period, and this strategy ensures that the portfolio of joint projects is constantly refreshed. For example, we have had three consecutive CASE studentships with DuPont Electronics (2002, 2006, 2011). In 2010, an EPSRC Knowledge Transfer Secondment funded three months at DuPont for one student post DPhil. DuPont state "*The immersion of the student into the scientific team created opportunities and an intellectual environment for high-level and sophisticated discussions into the particularly difficult questions that the DuPont team had in front of them. Critically, it is the detail that is important and without the immersion we doubt that some of the game changing thoughts would have been born. Furthermore, the student was integrated into the team and was able to contribute towards other questions that the team is also working on but from an applied mathematics viewpoint.*"

We often use small scale projects as a platform from which to grow more substantial industrial collaborations. For example, we undertook a short experimental project with e-therapeutics, a SABS-IDC partner. As a result of the IDC framework, we were able to identify a key piece of theory

whose application could have significant benefits for their business and e-therapeutics now fund a DPhil project to realise those benefits.

In some cases, collaborations can lie fallow for extended periods, but we endeavour to maintain contact. For example, our collaboration with Schott AG had been dormant for nearly a decade when informal discussions revealed that the work done then was now having significant impact and Schott have since agreed to sponsor a DPhil studentship in a related area.

Evidence of an agile approach to opportunities

(a) Opportunities for developing new relationships. Opportunities to develop new relationships can arise both serendipitously and through formal planning. The former often require agile approaches, usually taken from the menu presented earlier. As an example, in 2012 we were contacted directly by Pall (a 10,000-employee filter technology company). We organised one-day meetings in Oxford and at Pall's premises in the UK and the US. These scoping meetings led to a Pall-funded CASE studentship on membrane operation, an in-house Study Group where four filtration problems were addressed, and a Pall-funded fellowship which helped us retain a key research fellow.

A basic challenge is to transform new opportunities, which often arrive in an unformed state, into concrete collaborations. To achieve this, we ensure that our front-line staff have a sufficiently broad range of expertise that they can identify the appropriate specialists, either within or outwith our departments. For example, Thales brought a problem to our Industrial and Interdisciplinary Workshop and it was clear that the topic would be best addressed by members of our discrete maths group. A CASE studentship on graph-theoretic approaches to emitter-to-platform association is now in progress. We have an extensive network of contacts in other science departments, and in other universities, and we routinely involve them in our scoping meetings. For example, six of the academic participants in our meetings with Pall were from outside Oxford (four from the US).

(b) Opportunities for impact from existing research: The mathematical sciences provide the logical framework through which practical situations are turned into abstract concepts. The underlying models are an ideal conduit for technology translation. Insights previously gained in studying one application can rapidly be exploited in new situations, revealing connections where they are least expected. For example, AWE carry out experiments and simulations on violent compression of metals. When the applied pressure is much larger than the yield stress, we found that the metal flows like a compressible gas. Insight from our previous research in gas dynamics and hyperbolic systems was used to explain the experimentally observed behaviour, and provided a method for obtaining the effective equation of state for the metal from the experimental data.

Mechanisms for supporting, enabling, rewarding and recognising impact

We tailor the support offered to staff for achieving impact to their particular needs. For example, we seconded Donnelly (as Director) and McVean (as Director of Statistical Genetics) to the Wellcome Trust Centre for Human Genetics, where they have daily contact with researchers translating genetical research into clinical practice; and we seconded Lyons to direct the OMI, where he is co-located with Man's own research team. We granted special leave to one faculty member to enable him to gain practical experience of implementing computationally constrained estimation methods outside academia. Activities such as du Sautoy's "mathemagicians" or the Maths in the City project receive technical and administrative support. In 2013, we established an Office of External Relations and Public Engagement, with a Director and Manager. Our Research Support and Facilitation teams help staff engaging with industry, or otherwise exploiting research; ISIS Innovation (ISIS), Oxford's technology transfer arm, supports staff in exploiting intellectual property.

Senior figures are engaged in all our impact activities and they act as mentors and role models, helping to create a culture in which impact is valued and respected. We encourage applications, and proactively make nominations, for the University's impact awards, which recognise and celebrate the impact arising from Oxford's research, fostering and increasing awareness of impact. Seven awards have been made to UoA10 staff for: (i) substantial impact from a specific piece of research (Giles; Marchini); (ii) excellence in generating broad user interactions which have either achieved impact, or are conducive to achieving impact (Breward, Deane); and (iii) lifetime awards for successfully engaging externally and promoting impact (J Ockendon, Penrose, Ripley).

Using institutional facilities, expertise or resources in undertaking these activities

Oxford has invested heavily in mechanisms to enhance the impact of its research. In 2011, an Impact and Innovation team for the sciences was established, which supports and facilitates the development of cross-discipline relationships with large companies such as BP and Siemens. Initial contact is made at institutional level, before scoping productive scientific partnerships through which high impact research can be conducted. The University also provided funds for a Research Liaison Officer, whose remit includes broadening the industrial portfolio across the UoA.

Oxford's EPSRC Impact Acceleration Fund supports exploitation and impact of EPSRC-funded research, e.g. an award to fund a PDRA secondment to UCB Pharma and Roche Diagnostics.

Oxford's Department of Continuing Education provide access to wide-ranging expertise and technical and administrative support for our public engagement activities. For example, they helped provide du Sautoy with technical support for interactive online activities.

The University provides support for exploitation of research through ISIS, used by the members of the UoA for 4 patent applications (for allelic determination; loosely coupled distribution; method for tracking targets in video data; geometrical measurement of the critical micelle concentration of a water soluble surfactant) and 9 licences (for CHIAMO, GenoSNP, G-Tool, HAPGen, HAPQuest, IMPUTE, "quantifying flood risk", "Optimising pharmaceutical resource allocation", SNPTest). Oxford University Consulting (OUC) handles most academic consulting, negotiating the fee and indemnifying the consultant. All staff may undertake up to 30 days of consultancy per year without a reduction in salary. 54 consulting contracts have been undertaken by our staff during the reporting period. The University Research Services Office are heavily involved in the negotiation of IP terms with companies. They have negotiated 21 confidentiality agreements, and 31 industrial contracts.

Supporting and enabling impact through other mechanisms

Oxford is a major hub of the Knowledge Transfer Network in Industrial Mathematics, which connects companies with the UK Mathematical Community. J Ockendon and Please have chaired the KTN's scientific committee and we provide the academic base for several key KTN employees. We host the annual Alan Tayler Day for industrial mathematics; typically 20 companies are represented. More widely, we are proactive in promoting and attending Study Groups with Industry, with 69 faculty, 49 postdoc/research fellow and 59 student attendances, between them working on 116 problems from 73 different companies. We founded, host and maintain the (recently expanded) Mathematics in Industry Information Service (MIIS; www.maths-in-industry.org). MIIS has an archive of more than 500 reports on industry problems from more than 300 non-academic users, details of past and forthcoming Study Groups, and links to other Maths in Industry activities. Our influence on global Industrial Mathematics activity is also evidenced through the OECD "Report on Mechanisms for Promoting Mathematics-In-Industry", written in 2009 by J Ockendon.

We invite proposals from outside academia to embed non-academic researchers in our research groups, with the aim of developing relationships that may lead to impact, and to bridge the gap between academics and application areas. Six relationships of this type have taken place, including hosting members of small consulting firms and appointing visiting industry research fellows.

c. Strategy and plans

Our impact strategies, which were adopted mid-period, involve three key areas: promoting an environment conducive to realising impact; promoting impact through engagement with external organisations; and developing public engagement and outreach activities. Both departments have internal research strategy groups which routinely discuss impact, and means of achieving it.

Promoting an environment conducive to realising impact

Our overarching goals are to create an atmosphere in which achieving impact is an integral part of our research activities, and to provide support mechanisms which allow that impact to be realised. The mechanisms described in section b are used extensively by members of the UoA. However, they are constantly evolving, as is our research community, and so we will organise events to explain and promote the impact support available to researchers, especially targeting early career

researchers and new staff. As part of the internal process for grant support, applicants will be required to discuss their impact plan with nominated faculty members who have a proven track record in this area. Discussions of impact will be incorporated into our annual appraisal processes.

Promoting impact through engagement with external organisations

Four faculty members, Breward, Deane, Grindrod and Please, have a specific remit to support and build the range of interactions with industry. In 2012, we began a programme to develop relationships with external organisations through a part-time Impact Support Officer (ISO). Following the success of the scheme, we expect to make a permanent full-time appointment by late 2013. The ISO will ensure full implementation of our impact strategy, help the faculty exploit its research fully, maintain detailed records of our impact portfolio, develop promotional materials to articulate our impact to external organisations, and systematise the support we offer researchers in achieving impact.

Our new faculty bring new expertise, enabling us to engage with a wider range of users than hitherto. For example, expertise in data analysis will be applied in the retail sector. Two key goals for the next five years are to broaden our portfolio and to consolidate and grow our existing relationships. We work with several large multinationals: based on the success of our engagement with BP, we shall arrange that multiple projects with a given company are overseen by a single coordinator. This will ensure that productive relationships endure beyond personal contacts and increasing our capacity to develop new connections.

The Department of Statistics has just recruited an academic to extend the reach of its Consultancy Service, with a further appointment anticipated. This will increase the visibility of the Department as a centre of consulting for industry, government and the public. We believe our consulting activities have considerable potential for expansion and the appointees will drive this forward.

Our impact strategy has always been intimately connected with our training strategy and the recent award of CDTs in Industrially Focused Mathematical Modelling, Systems Approaches to Biomedical Systems, and Next Generation Statistical Science (joint with Warwick) will provide an ideal platform from which to develop wide ranging impact. Between them, these CDTs already have 65 partner companies who will be fully involved in every aspect of the graduate training and research.

Developing public engagement and outreach activities

The UoA already has extensive and high profile public engagement and outreach activities, but until recently this rested with a few key individuals. There is an increasing appetite for work in this area among our faculty. Our Director of External Relations and Public Engagement will coordinate and encourage an expansion of our activities and promote training opportunities. He is supported by an External Relations and Media Officer who will develop and implement plans to engage with the general public, work with charitable organisations, and raise the public profile of Mathematical Sciences. We have recently appointed two Schools Liaison Officers, one of whom will coordinate the work of Marcus' Marvellous Mathemagicians (student ambassadors for the beauty and relevance of maths) and expand it to properly reflect the importance of statistics.

d. Relationship to case studies

A number of our case studies exemplify our approach to achieving impact as described in Section b. For example, our Glass case study arose, in part, out of our strategies of involvement in Study Groups and engagement with industry through studentships. Our Risk On/Risk Off case study arose several years into our deepening relationship with HSBC, and it ran from underpinning research to impact within the assessment period. Our Moonshine and Cycles of Time case studies stem from our strategy to support public engagement. Our AIDS case study exemplifies our commitment to nurture relationships, to develop impact from current research, and to engage with policy makers. Our IMPUTE case study is an example of engaging with end users to develop impact from existing research. Our GCHQ case studies are classified but are consistent with our policy of enabling staff to engage in externally focused activities.