Institution:	University of Manchester (UoM)
Unit of Assessment (UoA):	B10 (Mathematical Sciences)

a. Overview

The UoA comprises the School of Mathematics (SoM) at Manchester, which is one of the largest unified mathematics departments in the country: 75 academic staff, 1167 UGs, 115 PGTs and 123 PGR students. It has had a long and distinguished history in pure mathematics (notably Adams, Mordell, Newman and Turing covering algebra, foundations of computer science, number theory, topology), applied mathematics (Goldstein, Lamb, Lighthill, Richardson covering continuum mechanics, waves, numerical analysis) and statistics (Priestley). The UoA sits within the Faculty of Engineering and Physical Sciences (EPS), which is composed of 9 Schools, over 600 academic staff and 70 specialist research centres and groups. The £40m bespoke Alan Turing Building is home to the UoA and places it, geographically and academically, at the heart of the University.

The UoA's size has enabled critical mass to be established across many areas of mathematics; thus, it is now home to world-leading research that both shapes the discipline and extends its reach. The UoA is divided, mainly for the purposes of teaching, into three groups: *Pure Mathematics*, *Applied Mathematics* and *Probability & Statistics*, although, as described below, the formal divides between areas are becoming increasingly blurred. Current research interests include the traditionally pure areas of algebra, analysis, mathematical logic, geometry and topology and, in applied mathematics, dynamical systems, fluid dynamics, solid mechanics, inverse problems, mathematical finance and waves. The UoA also has a strong tradition in numerical analysis and well established groups in probability theory and statistics together with the recent introduction of financial mathematics and actuarial sciences.

Noteworthy statistics and achievements over the REF period are

- 11 senior awards including Fröhlich Prize (Higham), Adams and Whitehead Prizes (Tisseur), Royal Society Wolfson Research Merit Award (Abrahams; Stafford)
- 140 keynote lectures delivered, 80 international meetings organised, 66 journal boards served
- strong interdisciplinary/industrial ethos with 15-fold increase in industrial funding to nearly £2m
- 16 new appointments including 12 early career researchers (ECRs)
- over 900 publications in top-rated journals (ECR adjusted average of 18 per member of staff)
- research income up 2.5-fold from RAE2008 (period adjusted) to £14.9m

b. Research strategy

Overview of Research Strategy and Vision

The UoA's overarching research strategy is, in simple terms, *to nurture and strengthen its core research across the breadth of pure mathematics, applied mathematics, and probability & statistics, while increasing engagement in intra- and interdisciplinary research and with industry*.

The strategy of the UoA is informed by and is consistent with *Manchester 2020*, the University's long-term ambitious strategic plan, which has permeated all levels of the Institution and drives strategic investment at Faculty and School level. The central pillars are Quality: *to achieve, and be recognised as achieving, research of the highest quality & capacity*, People: *to recruit, support and develop excellent people including PGR students,* and Impact: *to have an impact beyond academia which yields economic, social and cultural benefits.* To support the strategy are several enabling areas of action: *to provide focus, to capitalise on our critical mass and interdisciplinary capabilities*, and *to provide appropriate financial, physical and knowledge resources*.

The strategic direction of the UoA is underpinned by the UoM and EPS strategies, refined by the School Leadership Team and informed by annual operation and performance reviews, a SWOT analysis and periodic external reviews. Line management is organised from individual staff member, through topic leader and Heads of Groups (pure, applied, probability & statistics), to the Head of School. Research input is further provided by a Research Committee, Director (Higham) and Assistant Director (Parnell) of Research, internal funding Directors Wilkie and Abrahams, Director of Industrial Liaison (Evatt), and senior professorial staff.

Strategic aims and evidence of achievement

Mechanisms for and evidence of success of the aforementioned central pillars are now given.

1. Strategy: to achieve and be recognised as achieving research of the highest quality & capacity

As a consequence of the range of mechanisms for raising research quality, quantity and variety since RAE2008, which are discussed in Sections (c) and (d), there has been significant

improvement in scale of activity. For example, since 2008 over 900 research articles have been published, in contrast to 660 research publications during the RAE2008 (adjusted) census period. This amounts to an average of over 18 articles per submitted member of staff (adjusted for early career staff). Further, 157 grants were awarded to the UoA during the REF period, amounting to £14.94m in total, whereas for RAE2008 (period adjusted) there were 136 grants awarding a total of £5.6m. Of the submitted outputs for REF appearing in ERA ranked journals, 93% were in A or A* rated journals, up substantially from 82% for RAE2008. Exemplar research achievements are

- Gray set out a general theory for segregation of particles from any number of grain size classes. Experiment highlighted on the cover of Journal of Fluid Mechanics
- Paris: disproved the widely publicised Hawthorne-Makinson conjecture on the completeness of the Axiom System
- Premet: proved that the famous Gelfand-Kirillov conjecture on the structure of Lie fields (from 1966) fails for all simple Lie algebras of types other than A, C and G_2
- Stafford: classified noncommutative projective surfaces birational to commutative surfaces
- Juel determined that Hele-Shaw fingering can be suppressed by the presence of an elastic boundary. Editor's choice of Physical Review Letters

The UoA recognises the need for strong dissemination of its research outputs, as well as contributing to shaping the international knowledge base. Evidence of the way in which this has been enhanced includes the following. (i) *Publications* over 81,000 full-text downloads from the MIMS EPrints server in 2012. (ii) *Research visits and conferences* some 220 personal research visitors to the School; organisation of over 80 conferences and workshops in the Alan Turing Building, and 30 meetings elsewhere; contributions at 400 meetings, workshops and conferences (some 140 keynote lectures); and over 180 extended research visits to other universities. (iii) *Community work* over the REF period members of staff have served on 35 grant awarding committees, 66 editorial and other publication boards, and 18 national and international bodies. (iv) *Software* the UoA produces a significant amount of open source software, ranging from major packages such as oomph-lib, EIDORS, IFISS, LAPACK and NLEVP, to codes available on CRAN, the MathWorks File Exchange and personal web pages. (v) *Public engagement* a significant increase over REF in widening participation activities, with over 10 major events and initiatives.

2. Strategy: to recruit, support and develop excellent people including PGR students

Enabling strategies to support and develop staff and PGR students are the focus of Section (c). Evidence of success at recruitment can be seen by the 16 new appointments (12 ECRs) over the REF period in (i) areas targeted for growth (probability and financial mathematics, mathematical biology, and inverse problems), (ii) fields of excellence (e.g. numerical analysis) and (iii) interdisciplinary (e.g. tropical geometry) and industrial mathematics.

It is widely acknowledged that the life-blood of a UoA in Mathematics is its large and active graduate school. Healthy PGR numbers have been maintained despite reductions in staff numbers and EPSRC DTA support, with 201 PhD students and 125 completions over the REF period, up from a total of 170 registered PhD students and 99 completions during RAE2008 (period adjusted).

Evidence of the successful development of PGR students are 10 prizes and awards made to PGR students over the REF period, and 8 EPSRC Doctoral Prizes awarded over the last 3 years.

3. Strategy: to have an impact beyond academia

Since the creation of the new UoM in 2004, industrially focused research has had a very high priority within both the EPS Faculty and UoA. A number of enabling strategies have been employed to achieve our goals, including the appointment of Knowledge Transfer (KT)/Industrial Liaison Officers (Evatt & 2 new appointees); applications for strategic grants, such as MIRAN 'Building global engagements' grant (£498k) and MAPLE 'MAthematics PLatform Engagement activity' (£526k); and creation of a 'hub' model for industrial engagement (two arranged so far with Thales and NNSP).

As evidence of the success of the strategies, there has been a significant increase in range and volume of impact-led activity during the REF period. For example, approximately 10% of the total research outputs of the UoA are now directly inspired by industrial problems, and industrial-related income from all sources has grown to just under £2m during REF, up from £138k over RAE2008 (period adjusted). There has been substantial success in the take-up of available funding opportunities, e.g. over £1m (out of a total of £8.3m) secured from the University's EPSRC

Knowledge Transfer Account (KTA); 4 Knowledge Transfer Partnerships (KTPs) with NAG, Inventive IT and Argent & Waugh; long-term collaborations with imaging companies including Rapiscan and XRADIA (Lionheart, Dorn, Holman); grants from other industrial bodies including AWE (£164k), Dstl (£124k), National Grid (£143k), Federal Mogul (£75k), Fujitsu (£76k), Kraft Foods (£47k). Exemplars to highlight success of strategy are

- Abrahams & Parnell: first comprehensive approach to predicting the effective properties of composites with complex microstructure. CASE PGR & other support worth £330k from Thales
- Donev: developed effective correction methods for statistical analysis of data obtained in mixture experiments with mixing errors. PhD student support funded by Federal Mogul
- Lionheart: constructed, with an international group of clinicians and medical engineers, a unified algorithm for 2D linear EIT reconstruction of lung images. 2010 Martin Black Prize
- Higham: developed a new state of the art algorithm for computing the matrix exponential and its Fréchet derivative that is widely implemented and used, for example in the NAG Library and the Python package SciPy. Supported by NAG and KTP

4. Strategy: to provide focus and capitalise on our critical mass and interdisciplinary capabilities

The University, Faculty and School are committed to supporting world-class interdisciplinary research. The UoA has maintained longstanding links and created new collaborations with many cognate schools and sister universities. This has been achieved using a variety of enabling strategies to provide both funding and opportunities to develop internal and external collaborations. The UoA is also committed to breaking down historic barriers between mathematical disciplines, and has a track-record for successful intradisciplinary research. It recognises that intradisciplinary activity can stimulate and promote broad-based collaboration outside of the discipline. Evidence of success in both intra- and interdisciplinary research include

- Broomhead: used tropical mathematics to develop a new model which describes the movement of ribosomes on a strand of messenger RNA. Supported by CICADA Hybrid Dynamical Systems grant (EPSRC, 2007-12, £1.75m)
- Kambites: established a deep relationship between the multiplicative structure of tropical matrices, the geometry of tropical polytopes, and the algebraic structure of modules over the tropical semifield, leading to new insights into all three. Supported by CICADA and EPSRC
- Jensen: developed novel biomechanical models for plant cell walls and integrated these into a multiscale simulation tool for growing plant tissues. Supported by BBSRC funding
- Mullin: found, from theory and experiment in MCND (see Section (d)), a novel nonlinear elastic instability of periodic structures that can be used to develop smart materials. KTA support

5. Strategy: to provide the right financial, physical and knowledge resources

Both physical and knowledge-based research infrastructure are described in detail in Section (d). Since 2007, when the UoA moved into the Alan Turing Building, it has been able to provide world-leading facilities to its staff and PGR students in order to prosecute research. However, the success of the UoA in achieving its strategic aims is underpinned by a strong funding base. An enabling strategy has been *to maximise funding applications from as wide a variety of sources as possible*. Evidence of our success in industrial funding has already been mentioned, whilst that for core mathematical and interdisciplinary activity can be seen from the following exemplars

(i) RCUK grants: 'Nonlinear eigenvalue problems: theory and numerics' (Tisseur, £1.2m); 'Interpretation functors and infinite-dimensional representations of finite-dimensional algebras' (Prest, £598k); 'Optimal Prediction in Local Electricity Market' (Moriarty, £570k); 'MAPLE: MAthematics PLatform Engagement activity' (Abrahams, £526k); 'Tomographic Imaging' (Lionheart, £470k); 'Viscous fingering under elastic membranes' (Juel, £364k); 'EMS: analysis of numerical methods for PDEs with random data' (Powell, £344k); 'Multiple states of bubble propagation in partially occluded tubes' (Juel, £338k); 'Self organisation and run out behaviour of geophysical mass flow' (Gray, £335k); 'O-minimality and diophantine geometry' (Wilkie, £328k); 'The influence of nonlinear pre-stress on wave propagation through viscoelastic composites' (Parnell, £303k); 'Multiplicative structure of tropical matrix algebra' (Kambites, £302k);

(ii) non-RCUK grants: 'Functions of matrices: theory and computation' (Higham, ERC, €2m), 'Mathlogaps' (Logic group, EU, £387k), 'Deterministic and stochastic controlled systems and applications' (Zhang, EU, £330k), Royal Society Research Fellow (Eaton, 2008-11, £263k), 'Resilient energy networks' (Moriarty, National Grid, £143k), 'TUSL broadband hydroacoustics' (Abrahams, Thales & Dstl, £124k); 'Matrix Functions' (Higham & Tisseur, NAG KTP, £190k).

Future strategic aims and goals

In coming years, the UoA's research strategy will continue to develop as described above. Rather than attempt to pick winners in specific areas, we will provide an environment in which staff and students are encouraged and enabled to explore new ideas and address open problems. However, the UoA also recognises the need to reward excellence by recruiting into the successful research groups, and expanding into emerging fields, such as mathematical biotechnology and tropical geometry. The UoA sees impact-led activity as a critical element of a virtuous circle, whereby core mathematics is applied in novel ways and to new applications areas, which in turn identifies open mathematical issues that then inform new basic research.

Principal future goals of the UoA are to increase its international standing and be recognised as *the* leading centre in the UK for industrial mathematics. Enabling actions are to continue to improve citation performance through top-quality publications in highly-rated journals, increase collaboration with leading researchers worldwide, promote and support intra- and interdisciplinary research, and maintain the growth of income from a wide range of sources. The UoA will also seek to play an active role in developing the UK Government's eight great technologies.

c. People, including:

i. Staffing strategy and staff development

Staffing in relation to research strategy Consistent with the research strategy described previously, the UoA has a number of principles that guide its staffing strategy. These are, in all appointment and promotion decisions: to *recognise and reward excellence;* to *maintain or develop critical mass in key areas;* and to *enhance intradisciplinary interactions between existing areas of strength*. To illustrate these principles in practice in relation to new appointments in the REF period:

- 14 new lecturers have authored over 140 research publications within the REF period, of which 81% of their journal papers are published in A or A* ERA ranked journals, demonstrating that they are already producing substantial research at the highest level
- 3 appointments (Cotter, Guettel, Lotz) have broadened and strengthened numerical analysis
- the appointment of Jensen in mathematical biology opens significant new opportunities for links between applied mathematics, medicine, the life sciences and biotechnology
- 5 new appointments have grown interdisciplinary and industrial mathematics including mathematical finance (Parnell, Evatt, P. Johnson, Assier (from Dec. 2013) and 1 forthcoming)
- 4 new appointments have strengthened the probability & statistics unit in Lévy processes and random walks (Denisov), multiplicative chaos theory (Jin) and areas of actuarial science such as insurance (Loeffen, van Schaik). A further chair in statistics is presently being advertised
- other new appointments have contributed to critical mass in existing and emerging areas, e.g. algebra (Bazlov); inverse problems (Dorn, Holman); tropical geometry (M. Johnson)
- one forthcoming post in MCND will expand joint activity in experimental continuum mechanics
- two forthcoming lectureships in pure mathematics will reinforce key core areas

As with any successful and active school, a number of staff have taken promotion opportunities elsewhere since RAE2008 (Fielding, Grbic, Mazzocco, Neal, Plymen, Riedle, Ruban, Shardlow, Sharp, Taylor); there have also been 8 staff retirements and Buchstaber returned to Russia. As a consequence, research and teaching staff member numbers are down slightly from 78 in RAE2008 to 75 presently, although forthcoming appointments will shortly boost staff numbers to 81.

Career support and development - early career researchers The University offers EPSRC Doctoral Prizes giving up to two years of transitional support for researchers who have completed their PhD but want to develop an independent research career. The scheme includes a challenging career development programme, and mentoring support to help candidates achieve strong publications. The UoA has received 8 awards over the last 3 years from this highly competitive exercise.

All postdoctoral research assistants are closely mentored and encouraged to develop lecturing/tutoring and transferable skills. As a result, 15 PDRAs secured permanent academic positions over the REF period after completing their posts within the UoA. A probationary structure, leading to permanent employment, is in place for holders of long-term independently-funded research fellowships. We particularly support and encourage ECRs to take on PhD students. The UoM has an Implementation Plan to ensure full support for the **Concordat to Support the Career Development of Researchers**. In recognition, it has received the HR Excellence in Research Award from the European Commission. The UoM participated in the Careers Research Online Survey 2011 to find out the views of research staff and has incorporated the results into the

Concordat Implementation Plan, especially through staff representation on University committees.

Measures are in place to help early career academic staff develop their research programmes: reduced lecturing workload for their first two years; wide-ranging University and School mentoring schemes; attendance at the New Academics Programme (NAP). The latter, which must be passed by all new academic appointees before completing probation, covers teaching, personal skills, project management, and grantsmanship. ECRs also benefit from the website "*An Academic Career*", developed by the UoM Careers Service, which provides a comprehensive guide to working in higher education and was the winner of the Times Higher Education 2011 Award. The University also received the 2011 Scopus Fostering Young Researchers Institutional Award.

Career support and development – all staff Researchers have the opportunity to discuss and plan their career through annual Performance and Development Reviews and the EPS Researcher Development Programme (38 courses available). Further, Academic Promotions Masterclasses and Research Staff Conferences are held annually. Knowledge transfer and outreach activities are part of assessment criteria for promotion cases for academic staff, ensuring that time on such work is properly recognised and rewarded. The award-winning Manchester Gold programme matches participants to more experienced colleagues, who act as career mentors over a 9-month period. For senior researchers, the Headstart Programme provides training to develop leadership skills. As a result of these measures, over the REF period a total of 20 staff promotions were made (3 to Professor, 8 to Reader and 9 to Senior Lecturer.)

Staff members are relieved from administrative duties wherever possible, e.g. grant applications and post-award administration are supported by a dedicated finance officer. Staff members are strongly encouraged to take advantage of sabbatical (one semester for every 3 years served) and study leave opportunities. A total of 47 sabbatical semesters were taken over the REF period. The following research achievements demonstrate the value of sabbatical leave:

- Peskir: discovered the duality principle for the Legendre transform that yields the shortest path between the graphs of functions and embodies the underlying Nash equilibrium
- Symonds: proved Kemper's conjecture on degrees of generators of polynomial invariants and Benson's Regularity conjecture for cohomology of groups. MSRI and Leverhulme Trust Support
- Prest: unified the algebraic and model-theoretic approaches to definable additive categories by establishing an algebraic characterisation of the interpretation functors between these

The UoA has 5 dedicated Teaching Fellows (with an appropriate career progression path) whose main duties are to provide excellent teaching and to carry the major administrative roles associated with teaching and learning. Additionally, several recently retired staff members provide support through their continued research activity and teaching. A (transparent) workload allocation model ensures that all activities, including research, are fully taken into account.

Personal fellowships The UoA has been awarded 13 personal fellowships since January 2008: (i) Higham, ERC Advanced Grant (€2m, 2011-6); (ii) Eaton, Royal Society University Research Fellowship (£267k, 2008-11); (iii) Tisseur, EPSRC Leadership Fellowship (£1.2m, 2011-6); (iv) Moriarty, EPSRC Early Career Fellowship (£570k, 2013-7); (v) Dorn, RCUK Fellowship (£125k, 2008-13); (vi) Parnell, Faculty Fellowship (£120k, 2008-10); (vii) Cotterill, Royal Society Industry Fellow (seconded from Thales for 50% ~£200k, 2008-12); (viii) Jones, EPSRC Post-doctoral Fellowship (£218k, 2008-11); (ix) Bellamy, EPSRC Post-doctoral Fellowship (£225k, 2010-2); (x) Rodriguez Olmos, Marie Curie Intra-European Fellowship (£105k, 2008-10); (xi) Jensen, Leverhulme Trust Fellowship (£34k, 2010); (xii) Symonds, Leverhulme Trust Fellowship (£23k, 2012-4); (xiii) Hewitt, AWE - William Penney Fellowship (£312k, 2013-6).

International staff The UoA is an international community, with over 44% of staff originating from outside the UK. Overseas staff appointments in the REF period are Bazlov, Denisov, Dorn, Guettel, Holman, Jin, Loeffen, Lotz, van Schaik, and 4 of the staff who left the UoA were international appointments. Buchstaber held a fixed-term professorship to 2010. Additionally there were 70 overseas research MIMS visitors and 44 PDRA positions (out of 71) had non-UK PhDs.

Equality and Diversity The University is committed to the advancement of equality in employment and career development for its staff. Equality data monitoring and action planning is embedded into its annual performance reviews; this includes recruitment, current staff profile and promotion.

WiSET (Women in Science, Engineering and Technology), formed in 2005, is a network for all female students, technical, research and academic staff in EPS. It is funded by the Faculty and

aims to encourage more women to enter and develop careers in science, engineering and technology (SET) fields. It has strong links with the UK Resource Centre for Women in SET as well as industry. The UoA and UoM actively support the Athena SWAN charter; the University currently holds a bronze award and the UoA has applied for bronze status.

The UoM has been awarded the 'Two Ticks' disability symbol. This is a guaranteed interview scheme for disabled job applicants who meet the essential job criteria. The University has a dedicated support service for disabled staff.

The University is one of a small group of institutions that is part of the Equality Challenge Unit's Black and Minority Ethnic (BME) Systemic Change Pilot and is undertaking career development initiatives in relation to recruitment and mentoring.

ii. Research students

As mentioned in Section (b), the UoA firmly believes that a large and vibrant graduate school enhances the research environment within the UoA and we strategically target growth in both quality and quantity of PGR students. In 2012/3 there were 86 FTE PGT students and 123 FTE PGR students, making our cohort one of the largest in the UK. Registered PGR numbers over the REF period are: 120 (2008), 118 (2009), 127 (2010), 124 (2011), 130 (2012).

Recruitment of PGR students The UoA actively recruits outstanding PGR students from a wide variety of sources across the UK and internationally. The large and growing size of the UoA's UG and PGT (1167 and 115 FTEs respectively in 2013/4) cohorts provide a significant number of high quality taught students from which to recruit. The UoA has a wide range of PGT programmes in Applied Mathematics (new from 2012), Pure Mathematics and Mathematical Logic, Statistics, Mathematical Finance, and Actuarial Science. Numbers on these programmes have significantly increased since 2008, with 115 in 2013/4 (86 in 2012/3 increasing from 48 in 2008/9) and 43 MMath students in 2013/4 (45 in 2012/3 increasing from 33 in 2008/9). Between 2008 and 2012, 13% of MMath and 8% of PGT students went on to register for a PhD in the UoA.

The majority (74% since 2008) of PGR students come from outside Manchester. To recruit externally we run two nationally-advertised PG open days each year; however, our many contacts with other mathematics departments (both UK and international) means that most applications are generated via personal recommendations.

The University's commitment to supporting outstanding PGR students is demonstrated by the £2.5m President's Doctoral Scholar Awards (PDS Award) for over 100 elite scholars each year across the University. The Faculty also provides 10 Dean's Awards for outstanding PGR students. The UoA typically receives 2-3 PDS Awards and 2 Dean's Awards each year.

The UoA actively promotes interdisciplinary PGR projects with other Schools, including Electrical and Electronic Engineering (Moriarty), Manchester Business School (Duck, Peskir, P. Johnson), Materials (Dorn, Lionheart), Computer Science (Kambites, M. Johnson, Heil), Physics (Jensen).

School policy is to recruit and fund students based on their academic record and potential. This provides an equitable division of students across different research groups, with an average number of PGR students per academic of 1.89 (as of Oct 2012). Decisions on funding are made on a rolling basis, from February to July, allowing the UoA to be responsive to high-quality early applicants whilst maintaining flexibility to fund later applications. The UoA has flexibility to fund outstanding applicants applying to work with industrial partners, outside the normal cycle.

Sources of funding and funding allocation The UoA benefits from a large DTA allocation for funding home/EU students. However, it has strategically diversified its funding sources for PGR students. Notable sources include

- Other research funders at national and European levels: e.g. ERC (Higham), NERC (Gray), Leverhulme (Parnell, Abrahams), and the Marie-Curie funded MALOA programme (Wilkie)
- Scholarships funded or part-funded by industry. The UoA has a successful track record of supporting PGR students via CASE studentships (8 in total over REF), for example with Thales (Abrahams, Parnell) and NAG (Higham, Powell, Silvester). The UoA has also had notable success in arranging part or full industrial funding for PGR students (e.g. Arup, NAG, Rapsican, Thales, Cadburys, National Grid, BP, Federal-Mogul)
- The UoA actively recruits students via the University's CONACyT (Mexican) and Latin American PGR Programme agreements, with 5 CONACyT students recruited since 2010

In addition to external sources of funding, the UoA's commitment to a large graduate school is demonstrated by use of its own funds (£523k in 2013, rising from £300k in 2008) for PGR scholarships. This is used to fund UK/EU or international students. In summary, distribution of the total PGR funding received during the REF period is: DTA 45%, research grants 16%, SoM scholarships 27%, CASE (including DTA element) plus other industrial sources 12%.

PGR Training and Support Mechanisms The UoA ensures that all PGR students are trained in current research methodologies and have the opportunity to be trained in wider skills to enhance employability. Each PGR student is assigned a supervisory team comprising of a main supervisor (directing the programme of research), at least one co-supervisor (providing additional academic support), and an advisor (providing pastoral support). Training for supervisors is provided by the New Academics Programme (for new staff) and by Faculty researcher development courses (for existing staff.) Student feedback is received via the PG Staff-Student Liaison Committee, annual surveys e.g. PRES, and via electronic progression monitoring through eProg.

Breadth of training All PGR students are required to pass 100hrs of Taught Course Centre (TCC) material by the end of their 2nd year. The courses chosen are selected to strengthen the students' mathematical knowledge and to widen it beyond their research area. PGR students in pure and applied generally take courses from the MAGIC TCC Consortium (Section (d)) and the UoA's MSc programmes. Students in probability/statistics take courses from the Academy for PhD Training in Statistics TCC and the UoA's MSc programmes. All TCC/MSc courses have rigorous summative assessment which students are required to pass to progress on their programme of study.

Since 2008, PGR students have organised the annual 'Mathematics Research Students Conference' (MRSC) at Manchester, partially funded by IBM, featuring presentations and posters from current PGR students. They also set up a SIAM National Student Chapter in 2008 (3rd in the UK), which runs an annual 1-day meeting; attend the annual MAGIC PG Student Conference (inaugurated Manchester 2009); and run their own general and specialist seminar series in pure mathematics, applied mathematics and probability. Most students give at least three seminar talks (and many far more) during their PhD. The UoA supports PGR students in attending international research conferences and workshops by providing funds of up to £1500 per student per year.

Careers and employability The UoA ensures that its PGR students have access to training for a range of career paths. During induction, all students undergo a skills audit of existing competencies in both research and personal skills. Students also undergo training in generic transferable skills and have access to Faculty-provided 'Graduate Education' courses. There are employability events and courses organised within the UoA (e.g. on teaching STEM subjects in independent schools) and in Faculty, and in addition, students have access to the University's Careers Service.

Opportunities also exist in teaching and outreach work, both within the UoA (demonstrating in undergraduate courses and helping to run school liaison events such as the annual 2-day residential 'Making Maths @ Manchester' for over 100 sixth-form students) and externally (for example, training as a Maths Busker, designing and running workshops jointly with the Manchester Museum, and participating in 'Meet the Mathematicians' at the annual British Applied Mathematics Colloquium). One PGR student in the UoA is chosen per year to be a University-funded Widening Participation (WP) Fellow, devoting part of his/her time to outreach activities in the community.

The UoA actively encourages PGR students to undertake internships and placements with industrial partners. Many are generated by the Industrial Mathematics Knowledge Transfer Network and the UoA's Technology Translator. There have been 14 recent internships including with SkySports, Airbus, IBM Smart Energy, Dyson, Federal Mogul and AWE Aldermaston.

Monitoring The UoA has rigorous procedures in place for monitoring PGR students through their research programme. Each student's progress is monitored by eProg, an electronic progression monitoring system and skills training catalogue. Students complete quarterly progress reports on eProg and receive feedback from their supervisory teams. At the end of each year, students submit a report via eProg summarising progress made on their research project and write a plan for how the project will progress. The report is assessed by the supervisory team, an oral exam is held, and feedback is recorded on eProg. Progression into the following year is dependent on the report and viva being satisfactory.

Outcomes Submission rates within 4 years have improved year-on-year: 73% (2009), 81% (2010), 81% (2011), 83% (2012), due largely to improved qualifications of new PhDs, enhanced training

and support, and better monitoring. We expect further improvement as University regulations for students starting from 2012 prevent submission after 4 years. As evidence of PGR quality, ten prizes and awards were made to PGR students over the REF period, including UK Scopus Young Mathematician of the Year in 2011. Six PhD students had all-expenses-paid invitations to the annual SIAM Gene Golub Summer School. Over the REF period, Destination of Leavers of Higher Education (DLHE) records show 82% of UK & EU Maths PGR students secured paid employment.

d. Income, infrastructure and facilities

In mathematics, unlike many other areas of science, the critical research infrastructure and facilities are not just physical, such as buildings or experimental laboratories, but are also virtual, or knowledge based, e,g, in-house support or e-services. Both infrastructure types are listed below.

Physical research infrastructure

Alan Turing Building The UoA is fortunate in having an iconic and bespoke building in which to prosecute its research and teaching. It opened in July 2007, at a cost of £40m, allowing the UoA to continue to evolve throughout the REF period. As well as containing 100 staff and research offices and 19 large PG offices, it offers teaching rooms, large computing clusters, and dedicated space for its research dissemination and knowledge transfer arm, MIMS. The latter includes two seminar rooms, hot-desking area, Access Grid room, meeting rooms, and 5 multi-occupancy visitor offices.

MCND The Manchester Centre for Nonlinear Dynamics is the experimental arm of the UoA. It offers all staff members approximately 300m^2 of laboratory space, workshop facilities, equipment and technician support (0.75 FTE), shared with the School of Physics. MCND is led by Mullin and Juel with a core of 11 mathematicians and physicists. A broad range of nonlinear phenomena are investigated (currently in fluid mechanics, nonlinear elasticity and granular materials) using a combination of theoretical and computational modelling and quantitative laboratory experiments.

Access Grid The UoA hosts an Access Grid room, which allows advanced interactive videoconferencing sessions with other nodes around the world (and with individuals who have the necessary computer software). Access Grid in the UK has been supported by the Access Grid Support Centre (AGSC) at UoM until 2011, and since this time by the JANET Videoconferencing Management Centre. In addition to private research conference sessions, the principal role of the Access Grid room is to provide infrastructure for MAGIC taught course lectures.

The University of Manchester Library As a designated National Research Library, the UoM Library offers an unparalleled range of electronic resources for research including over 40,000 e-journals and a complete suite of research databases. Through the eScholar repository, it provides researchers with a premium resource to both deposit and disseminate their research outputs.

Underpinning (knowledge) research infrastructure

MIMS Research interactions and dissemination in the UoA are overseen by MIMS. It has specialist administrative support and a large dedicated area in the Alan Turing Building, described above, for organizing international workshops/conferences (over 80 held in 2008-2013), hosting visitors, running colloquia, and preparing and administering grants. A MIMS EPrints server advertises and disseminates research conducted by staff and associated researchers. MIMS supports, and acts as a focus for, internationally excellent research in mathematics at Manchester.

Continuing learning A very wide variety of regular research seminars are maintained by support staff dedicated to research activity within the UoA (a total of 10 weekly and 2 fortnightly seminar series). These include long-established series with external speakers and more informal seminars with mainly internal speakers drawn from staff and postgraduates. There are also informal series in dynamical systems, tropical geometry and waves, and many staff run their own reading groups.

MAGIC (Mathematics Access Grid: Instruction and Collaboration) This consortium of 19 Universities is the largest provider of taught course training to UK mathematics PGR students. Delivery is via Access Grid technology and lecture materials are freely available from its website. The UoA (Gajjar) has played a key role in the formation and development of MAGIC, being co-led (with Sheffield) from its inception in 2007 to 2011, and has been the sole lead since 2011. Participating nodes have all committed funding to MAGIC until 2016.

Interdisciplinary and industrial support A key element of the infrastructure supporting our interdisciplinary research is a Technology Translator/ Knowledge Transfer (KT) Fellow (Evatt). The UoA exploited the UoM KTA to create the position in order to liaise between industrial contacts and academics. This role was so pivotal that Evatt's position was made permanent in 2012 (as Director

of Industrial Liaison/ Lecturer in Industrial Mathematics). Further lectureships in industrial mathematics (Assier plus one other) will further enhance the UoA's KT activities.

UMRI and UMIP The UoA utilises a number of mechanisms offered by the UoM in relation to interdisciplinary research and impact. Examples are: the Manchester Research Institute (UMRI), which offers pump-priming for interdisciplinary solutions to societal and scientific challenges; and University of Manchester Intellectual Property (UMIP), the UoM's agent for IP commercialisation.

Investments in infrastructure and facilities

The UoM was created in 2004, following the merger of the Victoria University of Manchester and UMIST. The UoM is the largest single-site university in the UK, over 850,000m^2, with an annual budget of £809m, 10,700 staff and over 39,700 students. More than £750m has been invested so far since 2004 in state-of-the-art buildings, including the Alan Turing Building, and the UoM is embarking on new capital investment programme with an overall expenditure in excess of £1bn over the next 10 years. The latter includes a budget of more than £247m to locate, by 2018, all of the Schools in EPS onto a single site, with the UoA at its centre. The National Graphene Institute is presently being built adjacent to the UoA at a cost of £61m. The UoA benefits from the myriad high performance computing facilities offered by UoM Research Computing Services and N8 HPC, and the EPS Applications Support Team provides Condor clusters, training in languages and packages, and consultancy services to optimise codes.

Research funding portfolio

Over the REF census period the UoA was awarded 157 research grants worth £14.9m, with two in excess of £1m and four of £0.5m. The portfolio of grants from EPSRC amounts to £9.3m. Research awards from all major funding bodies are up significantly compared with RAE2008 (total £5.6m period adjusted), and were spread over a range of sponsors (REF; RAE08): RCUK (£10.7m; £5.1m); charitable bodies (£268k; £164k); European funding (£2.5m; £150k); industry (£912k, £138k); UK Government (£483k, £31k); other (£42k, £49k). Additional funding for sponsored studentships, including CASE, consultancy work and professional services brings the total industrial-related income earned to just under £2m. Of particular note is the fact that the UoA has reduced its reliance on RCUK research income and is approaching a more balanced portfolio; over the REF period, 72% of the income was from RCUK, compared to over 90% in the last RAE.

The UoA has proved agile over the REF period in obtaining substantial funding to underpin both interdisciplinary research and activity with direct impact on the non-academic community. Three particular exemplars are highlighted. First was the CICADA project (2007-11), directed by Broomhead and Glendinning, a £3m interdisciplinary Centre partially supported by a £1.75m 4-year EPSRC grant. Second, the UoA holds an EPSRC Platform Grant (MAPLE: MAthematics Platform Engagement activity, 2011-5, £526k) providing a responsive internal funding mechanism across the School for new intra- and interdisciplinary research activities. Third, the UoA has been developing a 'hub' based model for long-term partnerships with industry. Examples of this are with the National Nuclear Safety Programme (NNSP) (£312k) and the 'SMART' hub with Thales, for *pull-through* of existing collaborations and initiation of new topics (£150k).

As discussed in previous sections, and REF3a, the significant increase in research funding, especially in regard to industrial support, is evidence of the success of current UoA strategy. This will be continued and expanded in future plans, which are, in summary, to:

- increase the number of personal fellowship applications, especially from EU/ERC
- increase activity with other disciplines, e.g. life sciences & geophysics, and exploit existing links
- improve infrastructure to support preparation and implementation of research council grants
- expand industrial links and enhance existing partnerships, via Knowledge Transfer Officers

Consultancies

The UoA recognises the value of its staff undertaking consultancy and providing services for outside bodies, as long as it forms part of a virtuous circle, whereby basic research is applied to novel applications, which in turn identify open issues that inform new basic research. Since 2008, the UoA has provided consultancy services to some 17 companies (including Math Works, We Buy Any Car, British Nuclear Fuels) many of which have led to longer term research projects.

e. Collaboration or contribution to the discipline or research base

Support for research collaborations

The UoA has a wide variety of mechanisms to support and encourage collaborative research.

Core mathematical activity (i) MIMS, which supports visitor and workshop programmes (70 overseas visitors and over 80 international meetings during the REF period); (ii) a sabbatical programme (47 sabbatical semesters during REF period); (iii) University funding (including a £0.5k annual travel stipend); and (iv) joint supervision for all research students.

Intra- and interdisciplinary activity In addition to the above: (i) CICADA spanned Mathematics, Computer Science, Electrical and Electronic Engineering and Life Sciences (focused on hybrid discrete and continuous systems), attracting internationally renowned scientists and providing enhanced training to PGR students. (ii) MAPLE provides support for visitors, workshops, equipment, discipline hopping projects etc. MAPLE's rapid-response funding mechanism for pilot projects enhances the UoA's agility when responding to opportunities arising from industry, research councils or other external parties. MAPLE also supports additional Technology Translator time, and Creativity@home workshops. (iii) MCND, which encourages combined analytical, numerical and experimental research investigations.

Industrial activity Enabling mechanisms include: (i) Technology Translator(s), who introduced a number of initiatives to bring staff and industrial partners together, acting as a single point-of-contact; supporting colleagues when applying for funding; and initiating a programme of industrial study days (7 in the last two years). The latter has led to 13 MSc, PhD, PDRA and KTP projects to date, and provides an easy way for all members of the UoA to initiate interactions with industry. (ii) novel 'hub' support, allowing an industrial partner to bring an array of problems to a panel of staff, who will offer triage, assessment, and then handover to specialist staff. This provides a holistic service to users, and encourages a longer term relationship with the UoA. Income to the UoA from two existing hubs (£300k) is being used to create two new (permanent) lectureships. (iii) A wide range of other funding routes, including KTP, KTN, KTA, CASE awards, and full payment by the industrial partners. (iv) MAPLE and CICADA support, which foster novel interactions with industry and instigated the activity in tropical mathematics that spans pure and applied mathematics.

Summary and exemplars of collaborative research

Overview of collaborations Members of the UoA contribute to the global research base through national and international collaborations with researchers in well over one hundred different institutions across all six continents. The majority (60%) of the academic outputs are co-authored with external researchers; 20% of the total outputs in the REF period are in collaboration with other UK researchers and 40% are with international researchers. There were a total of 15 significant collaborative grants with other universities and industrial organisations (9 with a UoA lead) with a value of £2.21m attributable to the UoA contribution.

Significant interdisciplinary collaborations These include Muldoon's investigations with Bette Korber at Los Alamos on 'Mosaic HIV vaccines' (papers in Nature Medicine, PNAS and Virology and £51k grant income); Jensen's participation in 'EU AirPROM: Airway disease predicting outcomes through patient specific modelling' (€11.7m); Zhang's leadership of the Marie Curie Initial Training Network on 'Deterministic and stochastic controlled systems and applications' (€3.8m); Gray's collaboration with USGS allowing large scale experiments and fieldwork (grants totalling £645K from NERC); Moriarty's participation on an EPSRC Sustainable Energy Network Programme Grant 'The Autonomic Power System' (£3.4m); Pan's collaboration with Manchester Royal Infirmary on modelling cardiovascular disease (KTA grant plus £68k); Abrahams' role as UK coordinator for an Anglo-French Groupe De Recherche (GDR): 'Etude de la propagation ultrasonore en milieux non homogènes en vue du contrôle non Destructif' 2005–15 (support from various sources £260k).

Industrial engagement Partners span the energy (Alectrona Grid Services, National Grid, Electricity North West, BP Exploration, NAGRA, National Nuclear Laboratory Ltd), consumer (Kraft Food Ltds, Dyson, Unilever, Fujitsu), defence (Thales, AWE, DSTL), technology (NAG, Cambridge Display Technology, Inventive IT), transport (Airbus, ARUP, Federal Mogul) and health (Manchester Royal Infirmary, AstraZeneca) sectors. Approximately 10% of the total research outputs of the UoA are directly inspired by industrial problems.

Influence of collaborations on research activities and strategy

As discussed in Section (b), collaborations across disciplines within mathematics, with other disciplines, and with research users, is at the heart of our UoA strategy. Such collaborations have led to a significant overall increase in research activity and extended its reach and impact. The existence of many individual collaborations with industry has led to the development of long-term

strategic partnerships, such as with NAG, Thales and AWE. These successes have allowed the appointment of new staff at boundaries between research groups, at interfaces to other disciplines, with close links with industry, and with roles of knowledge transfer and technology translation.

Contribution to the discipline and leadership

Service on advisory boards Some 18 in total, including Abrahams: EPSRC Mathematical Sciences SAT & Board of International Council for Industrial and Applied Mathematics (ICIAM); Gajjar: Director of MAGIC; (2008-) and EPSRC TCC Course Directors Panel; Abrahams & Higham: REF2014 Panel; Jensen: Euromech Council Member; Glendinning: Member of Council for Mathematical Sciences (CMS); Wilkie: Sectional Committee 1 and the Prizes and Awards Committee of the Royal Society; Jensen: Director EPSRC Sandpit 'Maths of Life'; Abrahams & Stafford: LMS Prizes Committee; Borovik, Broomhead, Glendinning: IMA and LMS Councils.

Members of the UoA have served on some 35 grant-awarding committees, including acting as chair (Abrahams, Glendinning, Heil, Higham), in Austria, Canada, Croatia, Cyprus, Finland, Georgia, Germany, Ireland, Israel, Italy, Netherlands, Norway, Spain, Switzerland, UK and USA.

Election to fellowship & leadership roles in learned societies Abrahams (President Institute of Mathematics and its Applications (IMA) 2008-9); Borovik (Council Member LMS 2007-); Dongarra & Higham (inaugural SIAM Fellows 2009); Glendinning (Vice-president IMA 2011-3); Hammarling (Senior Honorary Research Fellow; SIAM Fellow 2012); Higham (SIAM Board of Trustees 2008-10, Vice President at Large SIAM 2011-3); Stafford and Wilkie (inaugural AMS Fellows 2012); Tisseur (Vice President UK & ROI SIAM Section 2013-5, Program Director SIAM Activity Group on Linear Algebra 2013-5, Board of Directors International Linear Algebra Society 2011-4); Wilkie (President Association for Symbolic Logic 2010-2, Elected Member Academia Europaea 2013).

Workshop and conference organisation at Manchester Over 80 workshops and conferences organised by MIMS since 1st Jan 2008. Major national and international conferences held in the UoA include the 2012 Logic Colloquium (Chair: Wilkie); British Applied Mathematics Colloquium (BAMC) 2008 (Chair: Abrahams); Conference on Stochastic Differential Equations 2009 (Chair: Zhang); Euromech Fluid Mechanics Conference 2008 (Chair: Duck); and Conference on Brauer's Problems – 50 years on (Chair: Eaton).

External conference organisation Conferences and workshops organised at prestigious international institutes include Interactions of Algebraic geometry and Noncommutative Algebra, Oberwolfach 2010 (Chair: Stafford); Program on Noncommutative Algebraic Geometry and Representation Theory, MSRI 2013 (Stafford); 1st and 2nd IMA Conferences on Dense Granular Flows, INI 2009 and 2013 (Gray); Algebraic Lie Structures with Origins in Physics, INI (Premet); Uncertainty Quantification, ICMS 2010 (Powell).

Keynote lectures Members of the UoA have given over 140 keynote lectures at major international conferences in their fields, and have contributed to over 400 scientific meetings; plenary examples are Doney (Stochastic Processes 2013); Gray (Powders and Grains 2013); Higham (Semi-Plenary at 6th European Congress of Mathematics 2012); Jensen (ICTAM 2008); Prest (International Conference on Representations of Algebras 2012); Wilkie (Clay Research Awards Meeting 2011).

Journal editorships Members of the UoA regularly contribute to the peer-review process, serving on approximately 66 editorial and other publication boards, and providing leadership as senior editors (6 in total), e.g. Managing Editor: International Journal of Theoretical and Applied Finance (Peskir); Executive Editor: Quarterly Journal of Mechanics and Applied Mathematics (Duck); Co-ordinating Editor: Annals of Pure and Applied Logic (Wilkie); Editor-in-Chief: Princeton Companion to Applied Mathematics and Editor-in-Chief: SIAM book series Fundamentals of Algorithms (Higham); Editor: IMA Mathematics Today (Broomhead).

Fellowships, awards and prizes Abrahams (Royal Society Wolfson Research Merit Award 2013-8); Dongarra (Career Prize of the SIAM Activity Group on Supercomputing 2010; IEEE Charles Babbage Award 2011; ACM-IEEE Computer Society Ken Kennedy Award 2013); Donev (Ziegel Prize 2009); Higham (Fröhlich Prize 2008); Loeffen (AXA Research Fellowship 2009); Lionheart (UoM Researcher of the Year Award 2012; co-winner IEEE Martin Black Prize 2009; Defence and Security Prize at Engineer's Technology & Innovation Awards 2010); Stafford (Clay Mathematics Institute Senior Scholarship 2012/3; Royal Society Wolfson Research Merit Award 2007-12); Tisseur (Adams Prize 2011/2; Whitehead Prize 2010).