Institution: The University of Manchester

Unit of Assessment: UoA11 Computer Science and Informatics

a. Overview

Computer Science research at Manchester is centred on the School of Computer Science, and has a long and distinguished history, including the construction of the first stored program computer in the late '40s, and the development of virtual memory among a range of innovations in the Atlas computer in the early '60s. Although we retain the practice of research driven by novel architectures, the unit now includes research in most major areas of the discipline and in several interdisciplinary fields. The unit is organised into 10 groups: Advanced Processor Technologies, Advanced Interfaces, Bio-Health Informatics, Formal Methods, Imaging Sciences, Information Management, Machine Learning and Optimisation, Nano Engineering and Storage Technologies, Software Systems and Text Mining. Several of these cross discipline boundaries (e.g. Bio-Health Informatics, Nano Engineering and Storage Technologies) and several others carry out research informed by interdisciplinary collaborations (e.g. Information Management in eScience, Text Mining in the life sciences, and Imaging Sciences in medical imaging). In addition, the unit hosts the Manchester Centre for Mesoscience & Nanotechnology, which played an important role in the discovery of graphene, for which the Nobel Prize for Physics was awarded in 2010.

The engagement in interdisciplinary research is reflected in this and other returns: 5 members of staff from the School of Computer Science have been included in the rosters of other UoAs (5 and 13), and this return includes 5 members of staff who have full or joint appointments in the Faculty of Medical and Human Sciences. This return is concentrated more closely on the core of the discipline than in RAE 2008, and as a result more staff from the School of Computer Science have been returned in other UoAs, and significantly fewer have been imported from other schools.

Highlights of the period include:

- Establishment of the only EPSRC Doctoral Training Centre in core computer science.
- Dynamic binary translation software shipped with 14 million Mac computers, supporting Apple's transition to Intel processors.
- A central role in the EU FET Flagship Human Brain Project, building on our SpiNNaker massively parallel computing platform.
- Success in 20 World Theorem Proving Championship divisions.

b. Research strategy

Vision

The unit aims to carry out *pioneering* and *outward looking* computer science research. By *pioneering* computer science research, we mean research that sets the agenda or tackles difficult problems within the discipline. By *outward looking*, we mean research that is informed by and tackles challenging problems in other disciplines. The strategy of the unit is not based on an attempt to pick winners in specific technical areas, but rather seeks to provide an environment in which staff and students are encouraged and enabled to explore new ideas and address open problems. Pioneering science is encouraged by ensuring that resources are available for exploratory projects through school-supported studentships, distribution of flexible funding to research groups, and thriving sabbatical and visitor programmes. Outward looking research is encouraged by making joint appointments between disciplines, enabling staff to locate themselves in research institutes, and by encouraging participation in interdisciplinary Doctoral Training Centres (DTCs). We provide examples of how the strategy supports the vision later in the section.

Strategy Development

The university strategic plan provides top-level strategies that inform policies and practices across the university. For example, the 2011/12 plan includes strategies to *value research excellence for its own sake*, to *broaden the range of funding sources*, to *provide parity of esteem to translational research*, and to *provide world-leading postgraduate research*. The Faculty of Engineering and Physical Sciences (EPS) strategic plan for research proposes finer grained objectives and indicators of progress. For example, to meet the university goal of providing world-leading postgraduate research, the faculty plan places an emphasis on the development of DTCs. This has been reflected in Computer Science through the establishment, with EPSRC support, of the UK's

only DTC in core Computer Science, as well as engagement in other DTCs. To ensure that the vision and ethos of the unit are reflected in university and faculty strategies, staff from the unit have served as Associate Vice President for Research (Taylor) and Faculty Associate Dean for Graduate Education (Miles) during the REF period.

The university operates an annual planning cycle that includes a review of progress against a wide range of key performance indicators, and the production of strategic and operational plans within schools. In computer science, strategic and operational plans are developed iteratively by the school leadership team in conjunction with the research, postgraduate research and external affairs directors, and are informed by discussions in away-days. A review of progress against these plans is a standing item on school leadership team agendas, so the progress and effectiveness of agreed actions are monitored regularly.

Strategies and Progress

Structured in terms of the top-level strategies of the university, this section focuses on specific objectives from the annual plans of the School of Computer Science, indicating how these support our vision, and providing evidence of progress since RAE 2008.

University strategy: to value research excellence for its own sake. This is in line with our vision to carry out *pioneering* research in computer science, which encompasses different models of intra- and inter-disciplinary research. Evidence of progress:

- To ensure that our strongest research is highly visible, staff have been encouraged to publish in outlets that are highly rated in the ERA rankings. The outputs included in this return include 69% A and A* Conferences and Journals from the ERA rankings (up from 55% in RAE 2008).

University strategy: to broaden the range of funding sources. In computer science, to enable engagement in larger scale projects with the resources to conduct pioneering research, and to strengthen outward looking collaborations, we have had two principal associated objectives:

- *To increase participation in EU projects*, we have established a role for an EU Coordinator, increased engagement in EU events, and run training on EU funding. Evidence of progress: total expenditure per anum on EU projects increased by 47% from 2008 to 2012.
- *To increase industrial income*, to ensure close engagement with industrially relevant problems, and to enable the direct application of research results. Evidence of progress: expenditure per anum on industrial projects increased by 45% from 2008 to 2012.

University strategy: to provide parity of esteem to translational research. This is fully in line with our vision for outward looking computer science research, and we have had several associated objectives:

- *To increase involvement in knowledge transfer projects*. Evidence of progress: during the REF period, we have been involved in 14 knowledge transfer (KT) projects with a range of partners, including the BBC, Greater Manchester Police, Unilever and Eagle Genomics; this contrasts with 6 KT projects in the previous RAE period.
- *To engage effectively with university centres that foster translational research*. Evidence of progress: during the REF period, 6 staff from the unit have been based in the Manchester Institute of Biotechnology; Hill from computer science has been the Facilities Director of the Manchester Centre for Mesoscience & Nanotechnology, managing the laboratory that is not only key to the unit's storage research, but that also enabled Manchester's Nobel Prize winning research on graphene; and Taylor has been director of Manchester Informatics, which coordinates translational research, in particular for Connected Health.

University strategy: to provide world-leading postgraduate research. In computer science, the aim has been to ensure that our research students have the time and training required to conduct pioneering research, and have access to interdisciplinary centres that support outward looking research. Evidence of progress:

- This has principally been achieved through increased engagement in DTCs, where the unit: hosts the £2.2 million EPSRC DTC in Computer Science; provides the Management Board Chair for the NowNano DTC; and has supervised 12 students from the BBSRC/EPSRC Systems Biology DTC and 7 students from the NowNano DTC. To ensure that we can recruit the strongest possible students, during the REF period, the School of Computer Science (in addition to funding from external sources for studentships) has invested on average over

£500K per year on research studentships fully or partially supporting over 70 students.

Further details on strategies and progress relating to people, infrastructure and collaborations are provided in Sections (c) to (e).

Examples of How the Strategy Supports the Vision

The vision of the unit is reflected in concrete cases:

- An example of *pioneering* research within the unit that *sets the agenda* is the development of the SpiNNaker parallel computing architecture that sets aside many of the assumptions of traditional supercomputers, to provide a massively parallel architecture for novel applications that is central to the EU FET Flagship Human Brain project.
- An example of *pioneering* research that *solves hard problems* is our research in automated reasoning that has developed techniques that bring many new problems, for example in program analysis, within reach, winning 20 world theorem proving championships in 5 divisions in the process.
- An example of *outward looking* research that *is informed by and tackles challenging problems in other disciplines* is our work on description logic languages, interfaces and tools, which has been informed by problems in eScience and medical informatics, and which underpins *de jure* standards for the semantic web, and supports the preeminent ontology tools and medical ontology standards.

In terms of our research strategy, these areas have between them benefitted from increased EU funding (£1.9M during REF compared with £0.22M during RAE2008) including an ERC Advanced Grant (Furber), increased industrial income (£3.76M during the REF period compared with £0.49M during RAE2008), full year industrial sabbaticals to Microsoft (Voronkov) and Siemens (Parsia), 5 academic appointments and 21 research students funded from the unit.

Future Plans

The unit's future research strategy will focus on support for the virtuous circle between fundamental computer science research and its use for solutions in application settings. The unit undertakes fundamental Computer Science research; this provides solutions to problems in applications from multi-disciplinary work that in turn provide challenges that stimulate fundamental Computer Science research. This virtuous circle has grown organically within the unit, especially in data science in areas such as computational biology and medical imaging. The unit's future research strategy will capitalize on this to enable researchers to stimulate curiosity-led research in a broad range of application settings that have scientific benefits for those settings, but are grounded in fundamental Computer Science research. This strategy will be realized by promoting studentships for research topics within the virtuous circle, encouraging models of collaborative research in the DTC, through engagement with the members of our industry club, through sabbaticals and extended visits, by encouraging different forms of result dissemination (software, online educational materials, public engagement), and through interaction with funders.

c. People, including:

i. Staffing strategy and staff development

Specific principles guide our staffing strategy, with a view to bringing about our aims to carry out *pioneering* and *outward looking* research. In all appointment and promotion decisions, we seek: (i) to recognise and reward excellence; (ii) to maintain or develop critical mass in key areas; and (iii) to open up interfaces between existing areas of strength. To illustrate these principles in practice in relation to new appointments: (i) our 9 new academic appointments have 56 publications in ERA A or A* outlets, thus demonstrating that they are already producing research at the highest level; (ii) our new appointments contribute to critical mass in areas of existing excellence for the unit, including computer architecture (Koch, Navaridas, Pavlidis, Pop), automated reasoning (Korovin) and nanoengineering (Vijayaraghavan); and (iii) the appointment of King in scientific automation strengthens the links between machine learning and the life sciences, and the appointment of Pavlidis from EPFL opens up new opportunities between computer engineering and nanoengineering in 3D circuits.

Career Development. Staff at all levels are encouraged to develop their skills, and during the REF period, staff from the unit participated over 300 times in training courses, in areas including project management, academic promotions, health & safety and leadership. In terms of research training,

the EPS Faculty Researcher Development team provides over 70 training workshops and events each year in 5 categories: Research & Enterprise, Communication, Career Management, Leadership and Management, and Teaching and Learning. For example, the 2011/12 programme included Project Management courses (leading to a Certificate in Applied Project Management), and the 2012/13 programme introduced a course on Supervising for Researchers. Over 20 staff from the unit have taken courses leading to Institute of Leadership and Management qualifications.

All new academic staff undertake the New Academics Programme, which involves around 50 contact hours over an 18 month period, and a collection of associated mentoring and development activities. The research elements include grantsmanship, managing a research portfolio, publication strategy, and postgraduate recruitment and supervision. In relation to knowledge transfer and impact, the programme also covers Intellectual Property Rights, collaborating with industry, regional development and public engagement.

New members of staff are introduced to key people, policies and resources through a school induction pack, and new academics have a personal mentor within the school, as well as a mentor associated with the New Academics Programme. To review career development and plans, the university implements a Performance Development and Review (PDR) scheme for all staff, which includes a written preparation document, a one-to-one discussion, and an agreed written conclusion. In the unit, software support for the PDR scheme was introduced during the REF period, and all members of academic and research staff are offered a PDR every year.

Concordat to Support the Career Development of Researchers. The university has developed a Concordat Implementation Plan that has received an HR Excellence in Research Award from the European Commission. The University 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 improving research staff representation on University committees. For example, Jay from the unit became a member of the Board of Governors of the university while a research associate. All researchers receive a Research Staff Handbook, and an annual Research Staff Conference provides up-to-date information and networking opportunities to research staff from across the University. Within the unit: the perceptions and needs staff have been captured through individual researcher meetings with the Director of Research and the school's Research Support Manager; a role has been created for an academic PDRA Champion; a weekly newsletter provides information on seminars, courses and funding opportunities, and also details successes such as research awards, publications and prizes, to keep the community up-to-date and to encourage collaborations; and thriving visitor/sabbatical programmes have enabled academic and research staff from the unit to increase their international contacts and exposure.

Research Fellowships. The unit encourages early career researchers to establish their research careers through fellowships, for example through reduced initial teaching loads, by integrating fellowships into the academic career track, and through sabbaticals. The following current staff have held personal research fellowships during the REF period: Korovin (Royal Society University Research Fellow, 2007-2012, with extension to 2015); Knowles (BBSRC David Phillips Fellowship, 2002-2008); Lujan (Royal Society University Research Fellow, 2009-2014); Navaridas (Royal Society Newton International Fellow, 2011-2012); Navarro Lopez (RCUK Academic Fellowship, 2008-2013); and Twining (RCUK Academic Fellowship, 2005-10). In addition, the following former staff held fellowships while at the unit: Barringer (RAEng Visiting Fellowship, 2008), Pękalska (EPSRC Research Fellowship, 2006-2009). We have promoted one member of staff during the REF period (Lujan) from Research Fellow to Senior Research Fellow (Senior Lecturer Equivalent) while still on a fellowship.

International Staff Appointments, Visitors and Sabbaticals. The school is an international community. For example, 41% of our research staff and 34% of our academic staff originate from outside the UK, and 60% of our research students originate from outside Europe. Reflecting the strong international profile of the school, 7 of the 9 academic appointments made during the REF period were from outside the UK.

To foster new collaborations and share best practice, the school has an extremely active visitor programme. During the REF period, 161 people from 34 countries held visiting positions in the school. These included visitors from international universities (e.g. Barcelona, Sydney) and from a wide range of commercial organisations (e.g. IBM, NHS, Imagination Technologies).

The unit also runs a sabbatical scheme; during the REF period, 24 staff have been on sabbatical (14 for a semester and 10 for a year), visiting international universities and research institutes (e.g. Max-Planck Institute for Computer Science, Barcelona Supercomputing Centre, Stanford, ISI California) and to industry (e.g. Wiley-Blackwell, Elsevier, Microsoft Research, IBM, Siemens).

Equality and Diversity. The University is committed to the advancement of equality in employment and career development for its staff, and equality data monitoring and action planning is embedded into annual performance reviews. In the unit, 25 members of staff have undertaken Equality and Diversity training within the REF period

WiSET (Women in Science, Engineering and Technology), formed in 2005, is a network for all female students and staff in the EPS Faculty. It is funded by the Faculty and aims to encourage more women to enter and develop careers in science, engineering and technology. Navarro Lopez has been both an invited speaker for WiSET and serves as a member of the 1st ACM-Women Europe Board (one of only two UK representatives).

To ensure that all groups are well equipped to engage with the promotions process, Academic Promotions Masterclasses are held annually. These sessions provide an overview of the academic promotion route at the University, the role of the School and the Faculty Promotion Committees, CV hints and tips (with the offer of 1:1 guidance), and academic promotions case studies. These have been attended by 8 people from Computer Science during the REF period. In the school, the following are the percentages of female staff at different levels/grades: PhD – 26%; RA – 15%; Lecturer – 33%; SL/Reader – 15%; Professor – 22%.

ii. Research students

The unit sees the development of the next generation of researchers as central to its mission. In line with our aim to conduct pioneering and outward looking research, the unit has increased its participation in DTCs that provide four-year programmes of research and associated activities, so that students have a strong basis both in generic research methods and in their area of specialism. The unit hosts the EPSRC DTC in Computer Science, which has recruited 37 students in its first two cohorts (15 in 2011/12, and 22 in 2012/13), and also participates in Systems Biology and Nanotechnology DTCs.

Recruitment. The unit has an External Affairs Office that manages publicity and student recruitment. The unit seeks to attract the highest quality candidates by advertising projects widely on www.findaphd.com, Prospects and on its own web site, as well as actively promoting research opportunities at graduate careers events. Applications are made online, and to ensure efficient processing of applications, the unit has developed a web-based platform for distributing applications and collecting feedback. The School receives applications from all over the world (34 different countries; normally ~70% overseas). Applicants for the DTC in Computer Science visit the school and are interviewed by a panel before an offer is made. The school has a thriving taught masters programme with 9 specialised pathways that align closely with our research strengths (with 148 students in 2012/13), and we have recruited an average of 8 students each year from our masters programmes into research degrees during the REF period.

To recruit the strongest students, the unit has spent an average of over £500K of its own funds each year in the REF period on research student support. In addition, an average of £535k per year comes from Doctoral Training Accounts and CASE awards (6 during REF period) across a range of Research Councils including EPSRC, NERC and MRC, recently supplemented with studentships from the EPSRC DTC in Computer Science. These funding sources are supplemented by University and Faculty schemes that currently support 5 students in the unit. For all funding sources, the primary selection criterion is the quality of the applicant. This support has enabled us to increase the number of new registrations for PhDs from 38 in 2008 to 56 in 2012.

Training and Support. Every research student has a supervisory team consisting of a main supervisor, a co-supervisor and an advisor; the two supervisors are responsible for technical guidance and progress, whereas the advisor is principally responsible for mentoring and pastoral support. In addition, volunteer student mentors run a mentoring scheme that includes: a hints and tips blog for PhD students; participation in an induction week; an annual welcome dinner and School-funded Spring day out; a yearly survey of PhD students; and sessions to help students prepare for their oral progression exams. PhD students are represented by the mentors on the staff-student consultative committee, which is an important feedback mechanism for students. The

unit has both traditional 3-year doctoral students, and 4-year students on DTCs (a total of 128 research students in 2012/13). The 3 year programme focuses on research excellence within a technical specialism, whereas the 4 year programme additionally provides a broader research training. These programmes share many common aspects: for example, the supervision model, several of the training units, progression mechanisms and a research students symposium. The shared training activities include an Introduction to Research, and 3 courses in scientific methods that cover all phases of a research project, from evaluation of the quality and importance of a research proposal, to the experimental verification and analysis of the outcome. DTC students also participate in technical modules, impact case studies, science in practice workshops, secondments and creativity workshops that build on the EPSRC's Creativity@home project. Although we value and will continue to offer 3-year programmes, the 4 year programmes have been designed to develop more complete researchers with a broader understanding of research lifecycles and strategies, and we anticipate that by 2014/15, half of our students will be on 4-year programmes.

A highlight of the school year is the Research Student's symposium, which includes presentations from all third year students, and a lively poster session with contributions from all second year students. Each symposium also includes a keynote speaker (e.g. Simon Peyton-Jones from Microsoft Research on *How to write a great research paper* in 2012) and sponsored prizes (currently by IBM) for the best thesis and paper that recognise and raise the profile of research student successes. During the REF period, our students have won prizes for their theses (e.g. 2012 and 2013 BCS/CPHC Distinguished Dissertation Award (Horridge, Pocock), 2009 BCS/CPHC Distinguished Dissertation Runner-Up and 2009 ICIQ Ballou Pazer Best Dissertation Award (Missier)) and papers (e.g. Best Paper Prize 22nd Intl. Joint Conf. on Artificial Intelligence (Nenov), Best Research Paper Award 7th Intl. Semantic Web Conf. (Horridge)).

Progress Monitoring. The online progression monitoring system, eProg, provides all research students with direction on the critical milestones for their degree. eProg captures engagement with training, and includes quarterly progress reports with elements completed by students and supervisors. Prior to progression to a new year of study, each student provides a written report that describes their progress and plans, and both gives a presentation and is interviewed by a panel. Where progress towards a PhD is not considered appropriate, there are exit points to research masters degrees (10 MPhils over the REF period).

d. Income, infrastructure and facilities

Infrastructure and facilities. The School of Computer Science is located in the Kilburn and IT Buildings, which provide 16,750m^2 of office, teaching and research laboratory space. These buildings are the subject of continuing improvements (e.g. the four main lecture theatres that are used for teaching in the DTC, for research events and seminars were refurbished in 2010). In addition, several investments have taken place to repurpose space for research use:

- *Laboratory space for Machine Learning and Optimization Research Group*. The unit has been growing its machine learning and optimization research activity (for example, through the appointment of King), and in 2009 the group moved into new office space as part of a comprehensive renovation of the ground floor of the Kilburn building. The new space includes 200m^2 of lab space, 11 offices and an 86m^2 seminar room.
- *Advanced Professional Education (APE) Suite*: Our APE unit develops research led training for commercial organisations and continuing professional development, and this training suite is used for face-to-face training, complementing and building upon research-based distance learning material developed by the unit with support from the BBSRC and EPSRC.

In 2012, Early Career Researchers in the School received 8 Small Equipment awards as part of the Faculty's £500K EPSRC Fund to update the Small Equipment Base for Early Career Researchers. In addition, each year the school provides a budget of over £200K to the research groups to support, for example, travel, equipment and research consumables.

Most of our research requires standard computing infrastructure which is supported by IT services teams at university, faculty and school level. The unit makes significant use of a Condor Campus Grid that provides access to around 800 machines with over 3000 cores, which has enabled the top 5 users from the unit to consume over 350 CPU-years; and Taylor for the unit is joint academic lead for the £3.25M N8 Centre of Excellence in High Performance Computing. Several of our research activities benefit from specialised infrastructure, and we have experimental laboratories,

for nanoengineering and storage research, and for scientific automation.

The Nano Engineering and Storage Technologies group hosts the cross-school *Manchester Centre for Mesoscience and Nanotechnology*, which as well as research in the unit on storage and nanodevices, is also a hub for collaborative work on nanotechnology, including graphene. Over the REF period upgrades have been made; for example, the class 100 areas now include a higher specification air-handling system, new doors and ceilings as part of a £5.3M EPSRC Science and Innovation award (2008). These upgrades have enabled the provision of a 24/7 facility and increased throughput. The purchase of a laser writer for preparing larger structures has doubled throughput; 6 new optical microscopes are in use, all with high resolution cameras and dark field imaging; two new deposition systems worth over £500K have increased the number of target materials; and a new Zeiss Ultra SEM provides more analytical capability and improved reliability. A new Bruker FastScan AFM enables rapid production of high-resolution images, and a state-of-the-art dry-etching facility for higher definition work and smaller structures is less hazardous than wet chemical processing and so more accessible for use, e.g., by PhD students.

The appointment of King was supported by the creation of a new *scientific automation laboratory* in the Manchester Institute of Biotechnology to support the development of advanced robotics and machine learning techniques that automate experimental design processes. The laboratory hosts two Robot Scientists. One of these, Eve, has been developed to automate and integrate drug screening, hit conformation, and QSAR development, utilising a combination of novel automation with synthetic biology assays, which enables much faster and cheaper screening.

The £1 billion campus master plan includes a new engineering campus adjacent to Kilburn, easing interdisciplinary research in areas such as computer engineering and nanotechnology; indeed an academic from the unit has a secondment to the National Graphene Institute to support the design of its laboratories, which among other things will support our storage and devices research.

Research funding portfolio.

In line with the university strategy *to broaden the range of funding sources*, and to support our vision of conducting *outward looking* research, the unit has sought to increase income from sources other than the research councils. In this context, the unit has increased expenditure per anum from other sources between 2008 and 2012 as follows: industry by 45% (from £625K to £911K) and EU by 47% (from £0.71M to £1.04M). In addition, comparing across the RAE2008 and the REF periods, income from charities has increased by 128% (from £236K to £539K). Such funding streams typically involve collaborations outside academia, and thus also increase exposure to emerging challenges and opportunities for impact. When taken together, the percentage of research income from sources other than RCUK has increased from 20% to 46%, and the percentage of staff in the unit with active grants has increased from 38% to 48%. We see this diversification of income sources and growth in academic participation levels as central to sustainability, and we will continue to encourage growing numbers of staff to maintain and develop relationships with a wide range of potential funders.

Consultancies and professional services.

Staff from the unit have consulted for a range of organisations as diverse as Microsoft (Voronkov), Fujitsu Labs Europe (Harper), QinetiQ (Nenadic, Keane), World Bank (Keane) and Theo Chocolate (Knowles). Taking the latter as an example, closed loop evolutionary multi-objective optimization techniques were applied to identify effective roasting strategies in an up-market chocolate manufacturer (J. Chromatography A. 2010; 1217(12): 1963-1970). In terms of services, the unit has offered high-profile computation services to different communities; such services include text mining services through Elsevier and Europe PubMed Central (Ananiadou, McNaught), and the widely used EasyChair conference management system (Voronkov). EasyChair has supported the reviewing process of over 20,000 conferences, and has over 800,000 registered users.

e. Collaboration and contribution to the discipline or research base

Collaborations (both within the discipline and outside, and geographically local and remote) are central to our aim to conduct pioneering and outward looking research, and many of our strongest research activities are intrinsically collaborative in all of the above respects (i.e. they involve both local and remote collaborations, with collaborators in computer science and beyond). This section first describes mechanisms that are used to foster collaborations, and then provides examples of collaborations, to indicate how the mechanisms support their formation, development and

sustainability in practice.

Supporting research collaborations. The unit has a wide range of mechanisms to support and encourage collaborative research. These include: a visitor programme (153 visits of more than 3 months during the REF period), a sabbatical programme (24 sabbaticals during REF period), a budget available to all researchers specifically for increasing engagement in EU programmes, over £200K support each year for research groups to use flexibly, and joint supervision for all research students. To encourage collaborations with industry, the unit has established an industry club with over 50 members, and the number of knowledge transfer projects has doubled compared with RAE 2008.

Supporting interdisciplinary research. All the mechanisms described above for research collaborations in general also apply to interdisciplinary research. In this section we describe mechanisms that specifically seek to support interdisciplinary research. These include participation in interdisciplinary DTCs (19 students in the school from such centres during REF period, all with joint supervisors from different schools) and engagement in interdisciplinary centres (currently 6 staff are based in the Manchester Institute for Biotechnology; 4 computer vision researchers are members of the Biomedical Imaging Institute; and Taylor from the unit is the Director of Manchester Informatics). Manchester Informatics, is a university research centre for interdisciplinary informatics that, for example, has established a Greater Manchester mHealth Ecosystem, a partnership of 50 member organisations from the NHS, local authorities and industry, committed to accelerating the uptake of mobile technology in health and social care. In addition, the unit has a long tradition both of joint appointments with other schools (currently 5) and of appointing staff who work in interface areas (a 2012 capability review showed that around a quarter of the staff in the unit are at an interface with another discipline).

Exemplars of Collaborative and Interdisciplinary Research.

We now describe several research areas for which collaborations are fundamental to their success, indicating how the above features of the environment have been applied in practice.

In *computer vision* (Cootes, Graham, Taylor, Thacker, Twining), the unit has significant collaborations in medical image analysis with physicians and pharmaceutical companies (income to the unit since 2008 = £5.2M). There is a deep integration with the NHS, in particular through collaborations with clinicians from local hospitals who are involved in framing problems, recruiting patients, organising and interpreting imaging. This complements a long-term collaboration with AstraZeneca on using image analysis to better understand disease and the effects of pharmaceuticals. Joint work with the Max Planck Institute in Ploen includes automatic landmark location in 3D micro-CT data and techniques for shape model construction. There has also been a long-term collaboration with Toyota on monitoring driver behaviour. Many commercial interactions are developed through spin-out company Imorphics; for example, new algorithms for building models from groups of images have been used by Imorphics to create accurate representations of organs that have won two international medical image segmentation competitions. This interdisciplinary area has been supported through 2 joint appointments between computer science and medicine, an RCUK Fellowship (Twining), 5 KTA awards, and a University of Manchester pump-priming award in mHealth.

In *e-Science* (Goble, Brass, Rector, Stevens, Pettifer, Attwood, Keane) the unit has developed techniques in knowledge management, virtual social collaboration, experimentation management, workflow execution and provenance that have been deployed in platforms by international initiatives in the Life Sciences, HelioPhysics, Biodiversity, Digital Preservation, Social Sciences and Clinical Systems. Income to the unit since 2008 = £13.6M. The Taverna workflow management system, developed with researchers in 5 UK Universities and more than 10 international research groups, has over 60K downloads during REF. The myExperiment online resource for sharing workflows has over 8000 registered users and 2500 workflows, and the BioCatalogue for Web Services (developed with EMBL-EBI) has over 2500 services from 188 providers. These platforms underpin the EU's large scale HELIO (HelioPhysics), Virtual Physiological Human, SCAPE (Library preservation) and Biodiversity Virtual eLaboratory infrastructures, and BioCatalogue is part of the EU BioMedBridges infrastructure. The UTOPIA Documents platform has over 50K downloads, and collaborations have led to its wide deployment, e.g., by Astra Zeneca, Pfizer, Springer, PLOS and The Portland Press. The e-Science activity has had extensive collaborations in gene identification, cattle breeding in Kenya, knowledge bases for kidney and urinary pathway research, standards for

healthcare and provenance (W3C PROV), and decision support for water distribution networks. This interdisciplinary area has been supported through 2 joint appointments with the Faculty of Life Sciences, 3 staff being located in the Manchester Institute for Biotechnology, 2 KTA awards, 21 visitors, an emeritus professorship (Rector), and 4 sabbaticals (e.g. at Oxford and USC).

In *human brain modelling* (Furber, Lester, Garside, Lujan, Navaridas) the unit has developed the SpiNNaker massively-parallel platform for modelling large-scale systems of spiking neurons in biological real time (income to the unit since 2008 = £7.75M). This novel computing infrastructure has been developed in collaboration with the universities of Southampton, Cambridge and Sheffield, and has recently attracted substantial additional funding from the ERC (€2.4M) and under the EU ICT Flagship Human Brain Project (€950k) to extend collaborations in the use of the platform to explore neural cognition. SpiNNaker hardware platforms are in use in the UK with the above collaborators and at Plymouth and QMU, in Europe at TU Munich, the Paris Vision Institute, EPFL and ETH Zurich, and in the USA at Johns Hopkins University. SpiNNaker has attracted wide publicity including IEEE Spectrum and New Electronics cover stories and featuring in "Through the Wormhole with Morgan Freeman" on the Discovery Science channel. This interdisciplinary area has been supported through 4 academic appointments in computer architecture/engineering, a Royal Society Fellowship (Lujan), 2 KTA awards, 16 visitors, and an extended visit to Lausanne for writing the FET Flagship proposal (Lester).

In *systems biology* (Mendes, King, Goble, Knowles, Paton) the unit has developed information management and analysis techniques and platforms in the BBSRC/EPSRC Manchester Centre for Integrative Systems Biology, which includes scientists from Chemistry, Chemical Engineering, Mathematics and the Life Sciences (income to the unit since 2008 = £1.66M). Results in genome scale metabolic modelling, optimization of experimentation, and experimental data management and integration have been informed by and applied in collaborations with life scientists. The COPASI simulation and analysis infrastructure developed with researchers in Heidelberg and Virginia Tech has had over 34K downloads and has over 950 registered users, and the SEEK system for managing systems biology data, models, and standard operating procedures, a collaboration with HITS (Heidelberg) and University of Stellenbosch (South Africa), is being used by two large consortia (the SysMO programme and the German Virtual Liver Network) and 7 other systems biology projects. The unit has led broad community collaborations to produce consensus models of yeast and human metabolic networks, and is playing a leading role in model and data management as part of ISBE (Infrastructure for Systems Biology Europe). This interdisciplinary area has been supported through a DTC in Systems Biology (12 students with joint supervisors from other schools), a new Chair (King), laboratory refurbishment for experimental automation, the housing of staff in the Manchester Institute for Biotechnology (King, Mendes), flexible appointments (Mendes holds a part-time appointment at the Virginia Institute of Biotechnology), and through an industrial sabbatical on experimental optimization (Knowles).

In *text mining* (Ananiadou, McNaught) the unit has hosted the National Centre for Text Mining (NaCTeM) since 2004 (income to the unit since 2008 = £3.21M). Results in scalable semantic methods such as parsing and event extraction, term normalisation and disambiguation, and learning for feature extraction have been informed by and applied by collaborations in the life sciences, systems biology and in publishing. NaCTeM web services were used over 750,000 times during 2012. A collaboration with Elsevier has led to the KLEIO, FACTA+ and Acromine text mining services being integrated into its SciVerse applications platform which has 10 million unique users per year, and joint work with the EBI and the British Library has enabled the users of Europe PubMed Central to benefit from services that include advanced semantic search informed by text mining. Interdisciplinary research at NaCTeM with the pharmaceutical industry (AstraZeneca, Pfizer) has developed advanced text mining techniques such as event extraction for drug discovery for angiogenesis and biological pathway reconstruction. This interdisciplinary area has been supported through a sabbatical visit to Elsevier, an emeritus professorship (Tsujii – now Principal Researcher at Microsoft Research Asia), bridging funding from the university to support transition from JISC centre funding to other sources, and 6 visitors.

Impact of collaborations on strategy.

Since well before the current REF period, the unit has recognised that its most significant research has often resulted from collaborations, both within the discipline and across discipline boundaries. Several of our strategic objectives from Section (b) seek to foster ever stronger collaborations: the

appointment of new staff at boundaries between research groups and at interfaces to other disciplines; the growing engagement in DTCs, several of which are interdisciplinary; participation in university research centres that typically focus on emerging areas and on translational research; increasing participation in knowledge transfer projects; and the growth of engagement in EU projects, all of which involve collaborations, many of which are with industry.

Leadership in the academic community.

This section provides examples of leadership roles that have been fulfilled by staff from the unit during the REF period. The unit encourages community engagement and leadership by providing groups with flexible funding for travel and community engagement, and by recognising key external responsibilities in its load model.

Advisory/Management Boards: 93 in total. Examples: Chen (Governing Board of IEEE Biometrics Council), Dongarra (Advanced Scientific Computing Advisory Committee for DOE Office of Science, Technical Advisory Board for the Numerical Algorithms Group, IEEE-Computer Society Fellow's Committee, IEEE John von Neumann Medal Committee), Furber (Chair of Royal Society Advisory Group: Computing in Schools), Goble (BBSRC Council, BBSRC Strategy Advisory Board, RAEng Leverhulme Trust Senior Research Fellowships Panel, Royal Society Wolfson Merit Awards Panel, European Research Council Advanced Grants Panel, IJCAI Advisory Board, EPSRC Programme Awards Panel Chair), Mendes (BBSRC Research Committee C, BBSRC Expert Working Group on Digital Organisms, US NIH Review Panel for National Centers for Systems Biology), Navarro López (IEEE-CSS Technical Committee on Power Generation Control, IFAC Technical Committee of Biological and Medical Systems), Paton (Extending Data Base Technology Executive Board), Sakellariou (Euro-Par Steering Committee), Schmidt (CADE Board of Trustees), Taylor (Board of European Connected Health Alliance, RAEng Research and Secondments Committee, EPSRC Healthcare Technology Strategic Advisory Team).

Editorial Board Memberships: 64 in total. The 17 in ERA A or A* Journals are: Ananiadou (Computational Intelligence), Chen (IEEE Trans. Neural Networks, Neural Networks), Cootes (IEEE Pattern Analysis and Machine Intelligence), Dongarra (Concurrency and Computation: Practice and Experience, Future Generation Computer Systems, J. Parallel and Distributed Computing, Parallel Computing), Keane (IEEE Trans Fuzzy Systems), Knowles (Evolutionary Computation), Lau (J. Applied Logic), Paton (VLDB J.), Pratt-Hartmann (J. of Logic, Language and Information), Sattler (J. Logic and Computation, J. Automated Reasoning), Taylor (Int. J. Computer Vision), Zeng (IEEE Trans. Fuzzy Systems).

Programme Committee Chair/Co-Chair/Track Chair: 46 in total. The 13 in ERA A Conferences are: Ananiadou (Assoc. for Computational Linguistics), Chen (IEEE-INNS Int. Joint Conf. Neural Networks), Goble (Int. Conf. Web Services), Harper (World Wide Web Conf.), Paton (Extending Data Base Technology), Sattler (Int. Joint Conf. Automated Reasoning, Int. Conf. on Principles of Knowledge Representation and Reasoning), Schmidt (Int. Conf. on Automated Deduction), Voronkov (16/17/18/19th Int. Conf. Logic for Programming, Artificial Intelligence and Reasoning).

Fellowships/Prizes/Awards: 59 in total. Examples: Ananiadou (IBM Innovation Award), Cootes (Fellow of Int. Ass. of Pattern Recognition), Dongarra (IEEE Medal of Excellence in Scalable Computing, SIAM SIAG/Supercomputing Career Prize), Furber (FRS, CBE for services to computer science; Millenium Technology Prize Laureate, RAEng Fellow, IEEE Computer Society's Computer Pioneer Award), Goble (RAEng Fellow, Microsoft Research Jim Gray e-Science Award), Keane (IBM Faculty Award), Korovin (Theorem Prover iProver: 7 World Championship titles in Theorem Proving), Voronkov (Theorem Prover Vampire: 13 World Championship titles in Theorem Proving), Zhao (IBM Faculty Award).

Keynote/Invited Talks: 63 in total. The 10 in ERA A or B Conferences are: Ananiadou (Int. Conf. on Intelligent Text Processing and Computational Linguistics), Cootes (Asian Conf. on Computer Vision), Furber (Design, Automation and Test in Europe), Goble (Intelligent Systems In Molecular Biology), King (Assoc. for Advancement of Artificial Intelligence), Korovin (Conf. on Automated Deduction), Voronkov (Conf. on Automated Deduction (twice), Int. Conf. on Computer-Aided Verification, Int. Conf. on Tests and Proofs).