Institution: The University of Nottingham

Unit of Assessment: Computer Science and Informatics (11)

a. Overview

Since its formation approaching 30 years ago, the School has embarked on an ambitious programme of investment and growth, and is now firmly established as a leading centre for Computer Science research. Our research is driven by an ethos of "computing in the world" that emphasises the grounding of fundamental research in real-world challenges and settings, while reaching out to other disciplines. Our core research is delivered by five research groups:

- *Automated Scheduling, Optimisation and Planning* (ASAP) – multi-disciplinary research on mathematical models and algorithms for real-world optimisation and scheduling problems.
- *Computer Vision Laboratory* (CVL) – multi-disciplinary research into computational techniques and software tools for image manipulation, image analysis and computer vision.
- *Foundations of Programming* (FOP) – foundational research on languages, techniques and tools for writing and reasoning about correct computer programs.
- *Intelligent Modelling and Analysis* (IMA) – computational intelligence techniques and tools for modelling and analysing large and complex data, grounded in real-world applications.
- *Mixed Reality Laboratory* (MRL) – drawing on human-computer interaction and ubiquitous computing to create interactive technologies that enhance everyday life.

We then maximise the impact of this research through major interdisciplinary research centres in partnership with other universities, industry and public partners:

- *Horizon Digital Economy Research Institute* (HORIZON) – a £40M national centre that combines a research hub, centre for doctoral training, and a network of 300 partners.
- *LANCS* – a £13M EPSRC-funded initiative spanning four universities with the strategic aim of strengthening and growing operational research in the UK.
- *CPIB* – a £15M centre that brings together computer scientists, biologists and engineers to tackle major challenges for the future of plant and crop science.

The strategic expansion of the School and the establishment of these new centres have seen us grow during this REF period to our current size of 47 academics, 49 researchers and 151 PhDs, receive research awards worth £24M to the School and £52M to the University, host 12 prestigious fellowships, appoint 9 early career researchers to their first lectureships, establish a £17M International Doctoral Innovation Centre at our China campus, produce 6 spin-out companies, and engage hundreds of thousands of members of the public in our research.

b. Research strategy

Our overarching vision of Computing at Nottingham focuses on engaging world-leading research with real-world problems. This involves a shared ethos of "computing in the world" in which fundamental advances in Computer Science are connected to knowledge and methods from other disciplines to enable deep collaborations with research users in diverse sectors. Our research is therefore strongly user-focused, interdisciplinary and impactful.

There have been two key elements to our research strategy during this REF period, both aimed at realising this vision. The first has been *growth of the School* through new staff appointments, promotions and the development of early career researchers, including the establishment of a new research group focused in the area of Intelligent Modelling and Analysis. The second has been strategic *leadership through interdisciplinary research centres* that connect our core Computer Science research to other disciplines, to leading research groups at other universities, and to industry partners. During this REF period we have been instrumental in establishing three major new research centres: the Horizon Centre for Digital Economy Research (including its Centre for Doctoral Training), the LANCS consortium in Operational Research, and the multidisciplinary Centre of Excellence for Plant Integrative Biology (CPIB).

Growth of the School. Following RAE 2008, the University adopted the strategic view that while research quality in Computer Science was very strong, it was now important to grow to achieve critical mass. This led to a strategic investment in new posts such that the School now has 47 members of academic staff (up 55% from RAE 2008).

Key external appointments have included the recruitment of two Professors (John and McAuley) and six Lecturers (Capretta, Lehre, Mortier, Valstar, Wagner, Wilson) from outside the University. Our commitment to developing early career researchers has seen the appointment of 9 talented research fellows (Atkin, Bacardit, Crabtree, Flintham, French, Greensmith, Ozcan, Parkes, Siebers) to permanent lectureships and the further appointment of 4 fellows (Coughlan, De Maere, Rennick-Egglestone, Soria) to part-time lectureships as part of their career development. In recognition of their excellence in research, 4 members of staff were promoted to Professor, 1 to Reader, 6 to Associate Professor and 7 to Senior Research Fellowships.

The effects of this growth are already apparent. The School now employs 49 research staff (up 60% from RAE 2008) and hosts 151 PhD students (up 60%). Research income has grown to £3.9M per annum (up 85%) and we have graduated an average of 23 PhDs per year (up 130%).

Leadership through interdisciplinary research centres. The School has a long tradition of working across disciplinary boundaries in order to pioneer new research areas. During this REF period we have pursued the strategy of bringing these into the mainstream through major new research centres in collaboration with funders and external partners. These operate across key boundaries with mathematics, social sciences, business, humanities and biosciences.

- *HORIZON* is a major centre for Digital Economy research established through £40M funding from RCUK, the University and industry partners. Its research focuses on how ubiquitous computing is generating lifelong personal contextual footprints of data and how these can enable new services across the digital economy. Horizon is the only UK Digital Economy centre to include both an RCUK research hub and a CDT. Part of the University's strategic investment in Horizon has been the appointment of Derek McAuley, a world-leading researcher with extensive experience in establishing both academic and commercial research labs, as Director. This key appointment has been enhanced with three 'Transitional Fellowships' that have taken exceptionally talented early career researchers on structured pathways into permanent lectureships in the School. Horizon has established a network of over 300 partners from industry, charities, artist groups and the public sector and acts as an incubator for major joint endeavours delivering impact across a range of domains including creative industries, energy and transportation. Horizon has also established an interdisciplinary research network that reaches into the business school, psychology, sociology and the humanities at Nottingham and at partner Universities including Cambridge, Exeter, Brunel, Reading and Glasgow.
- *LANCS* is a £13M (£5.4M from EPSRC) interdisciplinary initiative between the universities of Nottingham, Lancaster, Cardiff and Southampton with the strategic aim of strengthening and growing Operational Research in the UK in relation to complex and uncertain real-world problem solving environments. Our investment in LANCS has included the recruitment of Robert John as Professor of Operational Research and Computer Science, supported by 4 new lectureships and 5 fellowships. LANCS also connects to an international network of research and industry partners such as the National Air Traffic Control Service who are taking up the results of our research in the operation of Heathrow airport.
- *CPIB* draws together biologists, computer scientists, engineers and mathematicians to address plant and crop science questions. Established in 2007, CPIB has grown a network of over 50 researchers who work with international partners and companies and who have collectively drawn down over £15M of funding. The School's strategic investment in CPIB has included the promotion of Tony Pridmore to Professor, supported by the appointment of a new lecturer, to develop research at the interface of computer science and bioscience.

Research groups in the School. As well as investing in new collaborative initiatives, the School has also grown its core research base by investing in existing research groups and establishing a new group. Our four existing groups have strengthened their leading international positions through new staff appointments and major grant awards during this REF period.

- *Automated Scheduling, Optimisation and Planning* (Atkin, Bargiela, de Maere, John, Landa-

Silva, Lehre, Ozcan, Parkes, Qu; 9 research staff; 32 PhD students). ASAP conducts multi-disciplinary research into mathematical models and algorithms for real-world problems, together with fundamental theoretical research in optimisation and uncertainty modelling. During the REF period the group has produced 25 PhDs and published over 100 papers in leading international journals, including new results in airport scheduling, theoretical fuzzy logic, meta-heuristics, evolutionary run-time analysis, staff rostering and exam timetabling. ASAP is a lead partner in the LANCS initiative and the group's research has been commercialised by three spinout companies: Aptia Solutions (cutting and packing), Staff Roster Solutions (workforce scheduling), and EventMAP (timetabling and scheduling).

- *Computer Vision Laboratory* (Bai, French, Pridmore, Qiu, Valstar; 3 research staff; 22 PhD students). CVL conducts basic and applied research in image manipulation, analysis and computer vision. The group has produced 22 PhDs during the REF period, and through the pursuit of improved algorithmic techniques has developed new methods and tools in human behaviour analysis, visual tracking, feature detection, image segmentation, and face and medical image analysis. CVL's work on bioimage analysis featured in RCUK's keynote report "Big Ideas for the Future" and led to members holding senior leadership roles in the UK and European Plant Phenotyping Networks. Improved computer vision techniques developed by the lab have been central to a large number of interdisciplinary projects within CPIB, and underpinned the construction of the University's unique new £4M plant imaging facility.
- *Foundations of Programming* (Alechina, Altenkirch, Backhouse, Capretta, Hutton, Logan, Nilsson; 3 research staff; 19 PhD students). FOP aims to make substantial gains in the effectiveness of mathematical reasoning and apply such gains to the construction of correct computer programs. FOP's research in this period has addressed the three key areas of functional programming, agent-based systems, and algorithmic problem solving. The group graduated 16 PhDs and developed fundamental new results in type theory, program optimisation, categorical semantics, multi-agent systems, model checking, reactive programming, domain-specific languages, and algorithmic games. Members also played a leading role in the international community, serving as vice-chair of ACM SIGPLAN, editorial board member of the Journal of Functional Programming and Fundamenta Informatica, chair of the ICFP conference, and member of the Haskell language design committee.
- *Mixed Reality Laboratory* (Benford, Chamberlain, Crabtree, Flintham, Greenhalgh, Koleva, Marshall, Rennick-Egglestone, Rodden, Schnädelbach, Tolmie, Wilson; 21 research staff; 36 PhD students). The MRL has been integrating the fields of human computer interaction and ubiquitous computing to develop innovative digital experiences for everyday life. During this REF period the MRL graduated 27 PhDs and published 30 papers at the CHI conference (4 best papers; 2 honourable mentions), 4 in ACM Transactions on CHI, and 2 in Communications of the ACM. Members of the MRL have been awarded 5 prestigious personal fellowships and given keynotes at 10 major conferences. Collaborations with artists have produced performances that been experienced by 200,000 people in 18 countries. Members of the lab have chaired leading conferences including Pervasive 2008 and CHI 2010. Rodden and Benford were elected to the CHI Academy, and Rodden served on EPSRC TOP, SIP and SAN and currently chairs the advisory board of Microsoft Research Cambridge.

The School has also established a major new research group within this period:

- *Intelligent Modelling and Analysis* (Aickelin, Bargiela, Garibaldi, Greensmith, Siebers, Soria, Twycross, Wagner; 7 research staff; 32 PhD students). The IMA group has been established to exploit new strengths and opportunities in interdisciplinary computing and intelligent modelling. The group's work on novel complex data analysis, machine learning and decision support algorithms have created real-world impact in biomedical informatics (including a breast cancer spinout), security and the digital economy. During this REF period the group graduated 27 PhDs, and published over 150 journal and 250 conference papers. Aickelin has served in a number of leadership roles within EPSRC, as a member of the Strategic Advisory Teams for ICT and Complexity Science, leader of Ideas Factories in detecting terrorist activities and increasing UK productivity, and advisor at Future Leaders and Early Career workshops.

Future plans. Our future plans include a continued strengthening of our core research base alongside a further – global – outreach to new industry and academic partners throughout the

world. The School is currently growing a further research group in the area of Networked Systems around McAuley, Greenhalgh and Mortier to strengthen its core base. The recent renewal of the Horizon CDT will train a further 80 PhD students in close collaboration with industry partners who have pledged to support at least 30 co-funded studentships so far. The School also intends to broaden its international scope and collaborations over the coming years, especially with the burgeoning research activity in the Far East. We have recently made strategic appointments into our campuses in China (Qiu as Head of Computer Science) and Malaysia (Kendall as Vice Provost for Research and Knowledge Transfer) to drive this forward. Early evidence for the success of this internationalisation strategy includes the recent establishment of an International Doctoral Innovation Centre in China through an initial £17M investment from Chinese funders, the University and EPSRC, which will train a further 50 international PhDs in digital economy research.

c. People

i. Staffing strategy and staff development

The University gained the HR Excellence in Research award from the European Commission in 2001 in recognition of its commitment to research staff and to implementing the Concordat to Support the Career Development of Researchers. The 7 principles of the concordat are instantiated in the School's approach to proactively managing research careers at all levels from postgraduate students through to senior academic staff.

Postdoctoral staff and students are actively supported in their transition to academic posts and beyond. Research staff are given permanent contract status and managed within the University PDPR framework that involves regular career development meetings with senior academics to support the development of their research. They also take Careers and Employability Service courses to assist career planning. In order to proactively manage the transition to a full academic career we have partnered with the research councils to support 6 five-year Transitional Fellowships (3 within Horizon, 2 within LANCS and an RCUK fellowship) that provide phased transitions into permanent lectureships. We have recently extended this model to offer a further 4 part-time lectureships to allow early career researchers to gain valuable teaching experience as they transition to academic posts. These initiatives have been complemented by the provision of pump-priming research funds through Horizon, two EPSRC platform grants, an EPSRC Bridging the Gaps award, an EPSRC Cross-Disciplinary Feasibility Account and an AHRC Creative Economy Knowledge Exchange fund, all of which have been led by members of the School and have enabled research fellows to independently apply for and manage research grants and to experience sandpit style funding models. This approach to early career development has also helped shaped national initiatives, with Rodden mentoring the ICT event at EPSRC's Student Futures Programme. Evidence of the success of these initiatives includes 9 research staff in the School having transitioned to full-time lectureships during this REF period.

Early career academic staff benefit from reduced teaching and administrative loads (at least 50%) in their early years and the support of a senior academic mentor. They are also allocated an initial PhD studentship and provided with a seed budget to help them establish their research. The School's Grant Academy meets 6 times per year to advise new staff on preparing funding applications. More widely, the University has invested substantially in supporting early career researchers through the development of the Graduate School, which provides 60 training courses covering all aspects of career development for research staff and postgraduate students. Evidence of the impact of this support includes 5 EPSRC First Grants being held within the School during the REF period (Capretta, Koleva, Landa-Silva, Nilsson, and Radenkovic).

Established academic staff also have access to a dedicated research budget, supported through research margins, that supports initial feasibility research and travel to underpin larger proposals. All staff have an annual review meeting with a senior academic to make strategic plans for the coming year and select relevant staff development courses. Staff are also granted the opportunity to extend and refresh their research through the School's full-salaried study leave programme, which typically allows 1 semester of study leave in every 7. During the REF period, 10 members of staff (Altenkirch, Backhouse, Brailsford, Garibaldi, Greenhalgh, Krasnogor, Li, Logan, Petrovic, and Pridmore) received periods of study leave. Our international campuses also provide opportunities to develop research leadership, for example Kendall has been seconded as Vice-Provost of

Research and Knowledge Transfer for our entire Malaysia Campus, while Qiu has been appointed as Director of Digital Economy research at the £17M International Doctoral Innovation Centre at our China campus. Staff are entitled to 1 day per week for external and industry engagement which has supported visiting positions at the BBC and Microsoft and numerous consultancies, which have then led to industry funding and internship opportunities.

Rewarding excellence. The School and University recognise the need to reward excellence at all levels. Since 2008, 4 academic staff were promoted to Professor (Garibaldi, Hutton, Krasnogor, and Pridmore), 1 to Reader (Crabtree), 6 to Associate Professor (Brailsford, Koleva, Landa-Silva, Logan, Nilsson, and Qu), and 7 research staff were promoted to Senior Research Fellow (Chamberlain, Li, Marshall, Ochoa, Reeves, Schnädelbach, and Twycross).

Research fellowships. Staff are proactively supported in applying for personal fellowships and the School has been highly successful in this regard during the REF period, hosting 12 prestigious fellowships across all levels as summarised in section (d) below.

Equality and diversity. The University has 5 equality and diversity networks representing different groups that advise on workplace issues. In 2008, Greensmith was awarded an Anne McLaren Fellowship for outstanding early career female researchers and was subsequently appointed to a lectureship. In 2012, the University received an Athena Swan Silver award in recognition of its commitment to advancing the careers of female scientists, and in 2013 the School received an Athena Swan Bronze Award and hosted the BCSWomen Lovelace Colloquium. The School has a vibrant international outlook and culture, employing academic staff from 15 countries, recruiting 64% of PhD students from outside the UK, and enjoying close links with numerous international partners and our two overseas campuses. The Times Good University Guide 2012 described Nottingham as “the nearest Britain has to a truly global university”.

ii. Research students

The School attaches great importance to its PhD programme, which has been significantly expanded during this REF period. The total number of PhDs awarded was increased by 63% from 72 during the last RAE to 118 since 2008, and the average number of PhDs produced per year has more than doubled from 10 to 23. Recruitment has also doubled from 20 new students starting in 2008/09 to 40 new students in 2012/13, and the total number of PhD students in progress has now grown to 151. In 2009, the School played the leading role in establishing the £5.7M EPSRC-funded Horizon Centre for Doctoral Training, and in 2012 the £17M International Doctoral Innovation Centre at the University's campus in China as an extension of the Horizon CDT. The School also led the €2.2M CMIAG Marie-Curie European training network in Medical Image Analysis and participated in two further Marie Curie networks.

Recruitment. PhD applicants are normally expected to have a Masters degree or first-class Honours degree, and are funded from a wide range of sources including DTA and CDT funds, scholarships, grants, charities, and industry. The current PhD cohort of 151 students comprises 36% home, 17% EU, and 47% international students. By advertising attractive packages including enhanced stipends, doctoral training programmes, and industry internships, the School has been able to attract the highest calibre students. The School also runs an undergraduate summer internship programme, attracting bright undergraduates and giving them a taste of research.

Training and support. All PhD students have a primary and secondary supervisor, and undertake training in research methods, management and knowledge transfer through courses provided by the University's Graduate School, supplemented by a specialist 10-session course in Research Practice run by our PhD Course Director. Postgraduate students are represented on the School's Research Committee, and have the opportunity to gain appropriate teaching experience, supported by a dedicated 1.5 day training course. Students within the Horizon CDT and IDIC undertake an integrated programme of taught modules, practice-led research projects, thesis development sessions, and industry internships. Beyond the Horizon CDT, the School also plays a leading role in two national training initiatives for PhD students: the Midlands Graduate School in the Foundations of Computing Science (MGS), which provides a 5-day programme of courses in theoretical computer science, and the National Taught Course Centre in Operational Research (NATCOR), which provides advanced courses in operational research and computer science. The School also led the formation of the national Digital Economy Summer School (hosting the first in

2009) and has also hosted Summer Schools on Plant Bioinformatics, Systems and Synthetic Biology, and Image Analysis for Biologists. Students are allocated budgets to support attendance at conferences, workshops and doctoral colloquia. We were also recently awarded $50K by Google/YouTube to fund a PhD team-research project on crowdsourcing the coverage of marathon races. The strength of our training and support is reflected in students winning awards at major conferences, for example best paper nominations at ACM CHI and Ubicomp, and best paper awards at the TFP symposium and the Digital Economy All Hands Meeting.

Progress monitoring. The School has carefully designed, implemented and audited quality procedures for monitoring the progress of PhD students. First year students have probationary status pending successful completion of an end-of-year review that comprises an in-depth progress report and a viva voce examination with an independent assessor, and further reviews are conducted annually. Students meet with their supervisors on a weekly or bi-weekly basis, and are required to submit a minimum of 10 documented supervision-meeting reports per annum.

d. Income, infrastructure and facilities

Research funding portfolio. Research income into the School of Computer Science has increased from £15M over the 7 years of the previous RAE to £19.5M over the 5 years of the current REF, with the yearly average almost doubling from £2.1M to £3.9M. In total, members of the School were PI or CI on awards worth over £52M to the University. The school enjoys a healthy mix of funding from EPSRC, BBSRC, ESRC, AHRC, EU, Leverhulme, industry and public bodies, reflecting our strength in interdisciplinary working. This funding spans support for critical mass endeavours, platform support, PhD training, focused research projects, industry partnerships, personal fellowships, and community leadership:

Critical mass support underpins the major strategic initiatives described earlier and includes the £12.6M EPSRC Horizon Digital Economy Research Hub, the £5.4M LANCS initiative (one of the largest Operations Research grants in the world), and the University's £9.2M EPSRC/BBSRC Centre for Plant Integrative Biology. The School is also a key partner in major strategic initiatives that are led by other Universities including the ORCHID programme grant on Human-Agent Collectives (£5.5M, EPSRC, with Southampton and Oxford) and the CREATE centre for Creativity, Regulation, Enterprise and Technology (£4.1M, AHRC, led by Glasgow).

Platform support centres on two £1M+ EPSRC awards that underpin the work of the ASAP group and the MRL. Each platform award provides the stability for these groups to address key research themes, support the development of research staff and initiate new research endeavours that subsequently lead to support for focused research projects and fellowships.

PhD training support includes the £5.7M Horizon Centre for Doctoral Training (Nottingham is the only institution with both a digital economy research hub and CDT), hosting the €2.2M CMIAG Marie Curie network in Medical Image Analysis, and participating in the €3.5M MIBISOC and €2M BIOPTRAIN Marie Curie training networks. We also received funding for PhD training in the form of the National Taught Course Centre in Operational Research (NATCOR) (£240K, EPSRC), the British Colloquium for Theoretical Computer Science (£65K, EPSRC), and the Midlands Graduate School in the Foundations of Computing Science (£40K, EPSRC).

Research project support. The School received external funding for 120 projects worth £24M to the School and £52M to the University, supporting research across all of our groups. Many of these projects involve collaboration with other leading research groups in the UK and beyond. Examples include Automating the Heuristic Design Process (£2.6M, EPSRC), Homework (£1.5, EPSRC), Scaling the Rural Enterprise (£1.3M, EPSRC), Creating the Energy for Change (£1.1M, EPSRC), From Digital Record to Population Observatory (£700K, ESRC), Integrating and Automating Airport Operations (£660K, EPSRC), Networks as a Service (£550K, EPSRC), Modelling and Analysing Cargo Screening (£500K, EPSRC), three projects from the ICT for Manufacturing call (£6.5M, EPSRC), two synthetic biology grants (£1.7M, EPSRC), a €1.6M EU project on Energy-Efficient Architectural Design, and 5 ESPRC first grants (£540K).

Industry partnership support. We have participated in three major European Integrated Projects (iPERG, INSCAPE and MAGELLAN) and two STREPs during this period. TSB funding has included Participate, a major UK project with BT, BBC, Microsoft, Science Scope and Blast Theory.

We have been awarded 4 Knowledge Transfer Partnerships, while an AHRC Creative Economy Knowledge Exchange award has fostered engagement with the creative industries. We have received direct industry funding from Google, Xerox, Unilever, GE, NATS, Ordnance Survey, Yahoo and the BBC, complemented by funding from government agencies including The UK Border Agency, GCHQ and DSTL. Further details are provided in section (e) below.

Personal fellowship support includes 12 fellowships worth £4M from a variety of sources including a Senior Fellowship (Rodden), Advanced Fellowship (Aickelin), Dream Fellowship (Benford), Leadership Fellowship (Krasnogor) and Early Career Fellowship (Reeves) from EPSRC; a Royal Academy of Engineering Senior Research Fellowship (Li); an RCUK Fellowship (Crabtree); two Leverhulme Fellowships (Schnädelbach and Marshall); a HEIF Fellowship (Glover); an Anne McLaren Fellowship (Greensmith); and a Nottingham Research Fellowship (Twycross).

Community leadership support. The school has gained extensive support for research leadership and networking activities. This includes support for leading research networks: IT as a Utility (£1.5M, EPSRC), Ubicomp Grand Challenge (£254K, EPSRC), Integrated Behavioural Science (£4M, ESRC), Towards Pervasive Media (£200K, EPSRC), and Interdisciplinary Cutting, Packing and Space Allocation (£64K, EPSRC). These have been complemented by awards to promote new forms of research through Building Global Engagements (£500K, EPSRC) and Bridging the Gaps between Computing, Maths and Engineering (£350K, EPSRC).

The School will continue to build upon its established research strengths and diversity of funding. The visions of our research groups, grounded within a common ethos of "computing in the world", aligns with emerging research initiatives at a national and international level. We will continue to build upon our high impact research through initiatives such as Horizon and the newly established Connected Digital Economy Catapult (for which McAuley was appointed as Chief Innovation Officer). We will build upon our reputation for interdisciplinary research to become a collaborator of first choice across the scientific community where our technologies can be used as an engine of research. For example, image analysis work in the School has recently led to the formation of BBSRC's UK Plant Phenotyping Network, with Pridmore as Co-Chair.

Infrastructure and facilities. The School is located in a purpose-designed building on the University's award-winning Jubilee Campus, which provides a large and flexible space that is readily adaptable to our changing research needs. Each year the School allocates over £600K to PhD scholarships, provides £430K to research groups to support research staff, research administrators, and match funding on grants, together with an additional £220K to support travel, equipment, visitors, collaboration, seminars, away days, public engagement, and other strategic activities. The School leads one of the University's nine Priority Groups for research investment (Operations in a Digital World), which are key instruments in the University's Research and Knowledge Transfer Strategy. For example, through this scheme the University provided £9.5M of support for the Horizon Digital Economy Research Hub and CDT.

The University has invested substantially in High Performance Computing during this REF period. A new £1M system was purchased in 2008 and a £1.2M upgrade installed in 2013, providing a 2600 core system with a peak performance of 46 TFlops. Computer Science makes extensive use of this facility for large optimisation, search, simulation and data analysis problems in the ASAP, CVL, FOP and IMA groups. Nottingham is also a key partner on the £3.5M EPSRC-funded MidPlus regional high performance computing centre that was established in 2012.

In 2012, the School was awarded £500K from the University's Strategic Development Fund to establish the Advanced Data Analysis Centre to support research that involves large and complex data sets. The centre draws on novel algorithmic and analysis techniques developed in the School, and feeds back into our research by providing real-life data and case studies.

The CVL makes regular use of confocal laser microscope and X-ray micro-computed tomography facilities in the School of Biosciences, for which it has created a set of image acquisition and analysis tools, and associated hardware. CVL's development of computational methods for recovering 3D descriptions of plant roots from X-ray data underpinned the construction of the University's new £4M Hounsfield Facility, a unique centre that allows fully-automatic imaging of plant roots in their natural growing environment, and opens up significant opportunities for new research in 3D and 4D X-ray image analysis and informatics.

The MRL is based within a large reconfigurable lab space, which was initially established with £1.2M of JREI funding and updated with a further £1M under SRIF 2. This space is used for a wide range of design, construction and experimentation work, and the group also has a large shared pool of mobile devices and media equipment for use on research projects. The Horizon institute is based within a new building adjacent to Computer Science, and in keeping with its focus on future digital technologies makes extensive use of cloud computing facilities including Amazon Web Services (EC2, S3), Microsoft Azure, Memset servers and Flexiant servers.

The University provides a comprehensive range of central services to support the development of proposals, project finances, business engagement, technology transfer, and commercialisation. The School supplements this with a senior director of operations, research facilitator, finance officers, technical services and research administrators, and a grid access node.

Consultancy activities. Staff are supported to engage in consultancy work via the Nottingham University Consultants scheme. Key exemplars during the REF period include work with major tourist attractions on user experience (London Dungeon, London Eye, Thorpe Park, Alton Towers), public bodies on future technologies and research direction (JISC and the Connected Digital Economy Catapult), media organisations on user experience design, emotion recognition, interactive TV and advertising campaigns (the BBC and Lionsgate Films), software companies on game design and personnel rostering (Microsoft and Midland HR), public relations and advertising agencies on the use of new media (TBWA, Cake Group, and Havas Sports and Entertainment), and international airports on aircraft scheduling (National Air Traffic Services).

e. Collaboration and contribution to the discipline or research base

Research users. Our focus on computing in the word involves extensive engagement with research users from diverse sectors including the creative industries, transportation, energy, healthcare and security. Since 2008, we have worked with more than 450 individuals from 170 organisations across 25 countries. Collaboration has also been driven by the establishment of Horizon, with its network of over 300 partners, of which 64% have provided direct or in-kind contributions to over 70 collaborative research projects. As a result, user engagement has become deeply embedded into our research culture, and has grown to take many forms:

Partnership on research council grants. Research users are heavily involved in our research-council funded projects. For example, ASAP has engaged in a unique collaboration with the National Air Traffic Services NATS to deliver a new take-off time prediction system that has been running live at Heathrow Airport since 2012. FOP's close links with the Agda developer community resulted in key aspects of the language being based on the group's research, and the group's work on task scheduling was integrated into Jason and 2APL, two of the most widely used agent platforms. MRL's collaboration with Merlin, the worlds second largest visitor attraction company, has led to the deployment of new ride technologies at Alton Towers and Thorpe Park.

EU and TSB projects. These facilitate knowledge transfer through explorations of new products and services. For example, the MRL's collaborations with Sony and Nokia in an EU Integrated Project established the emerging genre of pervasive games, while collaboration with BT and the BBC on the TSB-funded Participate project developed a platform for mass media campaigns.

KTP's and industry funded research. ASAP have embedded their research expertise within four companies through KTP awards (Midlands HR, 3T Logistics, Microlise and Webroster). IMA have been supported by the information security arm of GCHQ to explore the assessment and modelling of expert variation in cyber security. ASAP have been directly funded by NATS. MRL has received direct funding from Google/YouTube, Unilever, GE, DETL, Yahoo and Xerox.

Spin-outs. ASAP has spun out three companies to commercialise its work on advanced optimisation and scheduling algorithms (Aptia Solutions, Staff Roster Solutions, and EventMAP), while IMA, CVL and FOP research resulted in spin-out companies to develop a clinical test for breast cancer typing (Nottingham Prognostics), automate and improve fertility analysis (Procreative Diagnostics), and provide a new platform for statistical computing (OpenBrain).

PhD training. Collaboration with industry is a vital element of the Nottingham PhD experience. CVL have engaged healthcare partners through its three Marie Curie training networks. Each Horizon CDT student undertakes an internship (examples include Microsoft, BBC and many

SMEs). GE is funding a PhD student and the BBC is supporting an EPSRC iCASE studentship.

Advising and consultancy. Our researchers also engage with industry partners in personal roles. McAuley was appointed as Chief Innovation Officer for the Digital Economy Catapult. Rodden has chaired Microsoft Research Cambridge's Technical Advisory Board. Benford was the BBC's first Visiting Professor. Numerous other consultancies are summarised in section (d) above.

Engaging citizens. Our collaborations with research users extend to engaging the public as the ultimate users of our research. Our collaborations with artists and cultural institutions have created interactive installations and performances that have toured to galleries, festivals, and museums in 18 countries, to be experienced by hundreds of thousands of visitors. Articles featuring our research have appeared on television shows such as Blue Peter (twice), Bang Goes the Theory, The One Show, and on the Discovery Channel, national and regional news, to be seen by many millions of viewers worldwide. Our bespoke public engagement videos, published on our Computerphile YouTube channel, have received more than 1 million downloads to date.

Academic collaboration and leadership. The School has engaged in extensive academic collaborations to lead the establishment of new research areas. We have hosted more than 200 visiting scholars from 20 countries, and appointed 6 academic and industry leaders to honorary professorships during this REF period. Examples of collaboration:

- ASAP has a longstanding partnership with Queen's University Belfast on timetabling research, which led to a joint spin-out. International collaborations leading to joint papers include with Maringa (Brazil), La Laguna (Spain), Monterrey (Mexico), Utara (Malaysia), Franche-Comté (Belgium - article in top 25 most downloaded in Information Sciences in 2012), and Shiraz (Iran). UK collaboration with Yao in Birmingham led to an article in Information Sciences.
- FOP research with neuroscientists in Leicester led to an article in Royal Society Interface and a spin-out company. International collaboration with Utrecht led to joint papers in Theoretical Computer Science and top AI conference IJCAI, with Kansas and Rosario to two articles in the Journal of Functional Programming, with Gothenburg to the widely-used Bove/Capretta method in type theory, and with Ottawa to an article in Lecture Notes in Logic.
- CVL research with Pompeu Fabra (Spain), Fudan and Sun Yat-sen (China) and Hong Kong Polytechnic and Baptist Universtities each led to joint papers in relevant IEEE Transactions, as did work with Schroder from Google. Collaboration with Xerox Research Centre resulted in a US patent and publication in Pattern Recognition, while two further patents arose from collaborations with the Hong Kong Applied Science and Technology Research Institute.
- IMA collaborators include Ellis, one of the world's leading breast cancer researchers, and Biganzoli (Milan) and Blazewicz (Poznan) in EU collaborative projects. UK collaborations with Hagras (Essex) led to a best paper in IEEE Transactions on Fuzzy Systems, while research with international leaders in fuzzy systems such as Pedrycz and Keller have resulted in many joint publications including a best paper award at FUZZ-IEEE.
- MRL's key international collaborators include Edwards and Grinter at the Georgia Institute of Technology through the EPSRC Homework project, and Kearne at Texas A&M University including a nine-month visit to Nottingham. UK collaborations with Sventek at Glasgow led to joint papers in ACM ToCHI and UIST, with Rogers at UCL to joint papers in ACM ToCHI and CACM, and with Giannachi at Exeter (Drama) to 2 joint papers in ACM ToCHI, 4 at CHI (with 2 best paper awards) and a cover article in Communications of the ACM.

Leadership in interdisciplinary research. Our commitment to extending the boundaries of Computing to engage with other disciplinary traditions and methods has been delivered through our involvement in the Horizon, LANCS and CPIB interdisciplinary research centres:

- Horizon has pioneered new interdisciplinary modes of working that combine Computer Science with the Social Sciences, Business, Arts and Humanities, leading the emergence of the 'in the wild' style of research which has since featured as the basis for EPSRC calls, while also embedding these approaches into PhD training through its Centre for Doctoral Training.
- LANCS has grown capacity at the interface between Computer Science, Management and Mathematics and has embedded the results into national PhD training (NACTOR).

- CPIB has developed the interface between Computer Science and Crop Science across European networks of collaborative partners.

Further evidence of interdisciplinary leadership is provided by substantial investments by non-traditional computer science funders. ESRC has invested in major eSocial Science programmes, AHRC in the CREATE centre for digital copyright and our Creative Economy Knowledge Exchange project, and BBSRC in synthetic biology and techniques to support plant science. These are complemented by investments by the EC in our three Marie Curie Training Networks that focus on the interface of computer vision to medicine and healthcare. We also co-edited Microsoft's 'Being Human 2020' report, with more than 15,000 copies distributed worldwide.

Esteem and evidence of success of research leadership. Evidence of the success of our academic leadership includes editing key journals, chairing major conferences, extensive advisory activities, invitations to give prestigious keynotes, and best paper awards that indicate landmark publications. Selected examples are provided below.

Journal editors-in-chief: ACM International Conference Proceedings Series, 2009-date (Rodden); Journal of Memetic Computing, 2009-date (Krasnogor). *Associate editors:* IEEE Transactions on Evolutionary Computation, 2009-date (Aickelin); Journal of Information Sciences, 2009-date (Bargiela); IEEE Transactions on Fuzzy Systems, 2010-2012 (Garibaldi); Computational Intelligence, 2007-date (Kendall); Soft Computing, 2013-date (John); International Journal for Information & Systems Sciences, 2009-date (John). *Editorial board members:* Fundamenta Informaticae, 2007-date (Altenkirch); Journal of Functional Programming, 2009-date (Hutton); Neural Computing and Applications, 2012-date (Landa-Silva); Journal of Memetic Computing, 2009-date (Landa-Silva); Journal of Evolutionary Computation, 2012-date (Lehre); Visual Communication and Image Representation, 2010-date (Qiu).

Conference chairs: Technical Program Co-Chair, ACM SIGCHI Conference on Human Factors in Computing Systems, 2010 (Rodden); Steering Committee Chair, ACM SIGPLAN International Conference on Functional Programming, 2010-2012 (Hutton); Editor-in-Chief, Genetic and Evolutionary Computation Conference, 2011 (Krasnogor); General Chair, International Conference on Artificial Immune Systems, 2012-2013 (Greensmith); Associate Program Chair, ACM SIGCHI Conference on Human Factors in Computing Systems, 2008 (Koleva); Symposium Co-Chair, IEEE Computational Intelligence in Scheduling, 2011 (Ozcan).

Leadership of professional bodies: Vice-Chair, ACM Special Interest Group on Programming Languages, 2009-2012 (Hutton); Member, UK Computing Research Committee Executive, 2010-date (Rodden); Task Force Chair, IEEE Computational Intelligence Society, 2007-2013 (Qu); President, European Council for Modelling and Simulation, 2010-2012 (Bargiela).

Steering and advisory roles: Chief Innovation Officer, Connected Digital Economy Catapult, 2013-date (McAuley); Member, EPSRC Strategic Advisory Network, 2011-2013, Societal Issues Panel, 2009-2011, Technical Opportunities Panel, 2005-2009 (Rodden); Member, EPSRC Strategic Advisory Teams for ICT and Complexity Science, 2009-date (Aickelin); Management Group Chair, Framework for Innovation and Research in MediaCityUK (FIRM), 2010-date (McAuley); Chair, Scientific Advisory Panel for Mobile Life, Sweden, 2010-date; Chair, Technical Advisory Board of Microsoft Research Cambridge, 2010-date (Rodden).

Keynotes and plenaries: Royal Institution, London, 2010 (Greensmith); International Conference on Collaboration Technologies and Systems, Pennsylvania, 2011 (Benford); International Conference on Mathematics of Program Construction, Canada, 2010 (Backhouse); International Fuzzy Systems Association World Congress, Indonesia, 2011 (Bargiela); International Conference on Parallel Problem Solving from Nature, Poland, 2010 (Garibaldi); Genetic and Evolutionary Computation Conference, Philadelphia, 2012 (Lehre); IEEE International Conference on Pervasive Computing and Communications, Seattle, 2011 (McAuley).

Best paper awards: ACM SIGCHI Conference on Human Factors in Computing Systems (2009, 2011, 2012, 2013); IEEE Transactions on Fuzzy Systems (2010); IEEE International Conference on Fuzzy Systems (2012); International Symposium on Trends in Functional Programming (2011); Journal of the American Society for Information Science and Technology (2009); Genetic and Evolutionary Computation Conference (2008, 2009, 2010, 2011).