Institution: University of Oxford

Unit of Assessment: 11 (Computer Science & Informatics)

(a) Overview

Since RAE2008, the Department of Computer Science at the University of Oxford has vigorously pursued the ambitious programme of development and expansion that was initiated following RAE2001. This programme has seen the department continue to diversify its research portfolio far beyond its historic origins in programming language theory and numerical algorithms, and, indeed, our change of name in 2011 (from "Computing Laboratory" to "Department of Computer Science") was intended to signal this fundamental shift in scope, scale, and ambition. The continuing dramatic improvement in the quality of our research environment is evidenced in many ways, for example:

Grant Income Growth: For the REF2014 period we report a total research grant expenditure of £52.2M – up from the £9.5M total we reported for the RAE2008 period. This is nearly a six-fold increase in research grant expenditure compared to RAE2008. Our REF2014 grant expenditure per FTE (£710K per FTE returned) exceeds that of any institution returned in the corresponding UoA for RAE2008.

DPhil Students: We have awarded 124 DPhil degrees (University of Oxford PhDs) in the REF2014 assessment period, compared to the 54 we awarded during the RAE2008 period: more than a twofold increase in DPhils awarded per annum compared to RAE2008.

Citation Record & External Rankings: According to Microsoft Academic Search, over the past five years Oxford University has been the top-ranked UK institution for computer science research when measured using total citation count (see http://tinyurl.com/CSOxfd01), and we have been the top-ranked European institution for computer science over the past five years when measured using the *h*-index (http://tinyurl.com/CSOxfd02). The Shanghai Academic Ranking of World Universities (ARWU) has placed Oxford University first in Europe for computer science research every year since 2009 (http://tinyurl.com/CSOxfd03). The 2013 QS World University Rankings place Oxford University third in the world for computer science and information systems, and first in Europe (http://tinyurl.com/CSOxfd04).

Prestigious Publications: In the REF2014 period, staff in this UoA have published in many prestigious venues, with the following being of particular note: 10 papers in *Journal of the ACM* (JACM – the most prestigious international venue for computer science research); 17 papers in the *ACM/IEEE Symposium on Logic in Computer Science* (LICS); 13 papers in *Artificial Intelligence Journal* (AIJ); 12 papers in *Journal of Artificial Intelligence Research* (JAIR); 20 papers in the *International Conference on Computer Aided Verification* (CAV); 30 papers in the *International Conference on Automata, Languages, and Programming* (ICALP); 28 papers in the *International Joint Conference on Artificial Intelligence* (IJCAI); and no less than 10 papers in *Nature* journals, with the latter clearly demonstrating the excellence of our interdisciplinary research.

Investment in People: Since RAE2008 we have made nine external professorial appointments, and appointed 18 lecturers: we here return 73 FTE staff (compared to 56 in RAE2008).

New Research Themes: Since RAE2008, we have opened up two major new research themes – Algorithms and Security – supported by nine new academic appointments.

Fellowships of Learned Societies: Two staff returned here were elected to Fellowship of the Royal Society (FRS) in the REF2014 period, three to Fellowship of Academia Europaea, and one to Fellowship of the Royal Academy of Engineering (FREng).

The overwhelming bulk of this submission is from Oxford University's Department of Computer Science, although we also return a very small number of staff from other units within the university: 3.2 FTE from the Oxford e-Research Centre (OeRC); 1 FTE from the Oxford Internet Institute (OII).

(b) Research Strategy

OVERALL AIMS: The overall aim of the Department of Computer Science is to be a world-leading centre for research and teaching in contemporary computer science, with a research portfolio that runs the gamut from pure theory to deployed applications. We aim to deliver impact through research that directly addresses the present and future needs of industry, commerce, government, and society. A fundamental characteristic of our vision for computer science is that all research should be underpinned by rigorous foundational principles. An overarching goal of the department over the past decade has been to progressively expand its research portfolio beyond its origins in numerical algorithms and programming language theory; as the range of research returned here indicates, enormous progress has been made towards this goal. Research in the department is focussed around seven research themes (described below), providing a constructive and pro-active management structure within which staff and students carry out their research. Significant effort is devoted to ensuring that the themes do not operate as silos: many staff members are active in more than one theme.

RESEARCH STRATEGY DEVELOPMENT, IMPLEMENTATION, AND MANAGEMENT: The formulation, implementation, and management of research strategy is the responsibility of the department's Research Committee. The primary strategic responsibilities of the Research Committee are as follows:

Research Theme Development and Maintenance: Research themes are determined both strategically (typically emerging research areas that the Research Committee determines will be of lasting importance, and which present substantial research challenges), and by developing successful growth activities from current research themes. Following RAE2008, one completely new theme was identified for investment in the REF2014 period: Algorithms (leading to the appointment of Professors L. Goldberg, P. Goldberg, and Koutsoupias). Significant investment was made in Security, establishing this as a theme in its own right, with the appointment of Professor Creese and four lecturers. Investment in artificial intelligence led to the appointment of Professors de Freitas and Wooldridge. The Computational Biology and Programming themes were significantly enhanced by the appointment of Luca Cardelli as a joint Oxford-Microsoft Royal Society Research Professor. In addition, Oxford University's large postgraduate Software Engineering Programme was brought under departmental management, and expanded from 9 to 14 academic staff.

Appointment of New Staff: Senior staff appointments are typically made with the goal either of establishing new research themes or of building up leadership strengths in existing themes. Junior appointments are primarily used to reinforce research strengths in key areas, and build synergies within existing groups. More detail is provided in section (c).

Research Income: Research income was identified as a priority issue following RAE2001, and the department's research income increased continuously throughout the RAE2008 period. This growth has continued apace throughout the REF2014 period. Apart from simply expanding the research funding base of the department, the single most important aim of the department's research income strategy was to diversify the portfolio of research funding, and in particular to avoid over reliance on a small set of research funders in economically uncertain times. The range of funders of our research in the REF2014 period is clear evidence of the success of this approach. More detail is supplied in section (d).

PGR Student Funding, Recruitment, and Oversight: The Research Committee has overall responsibility for advertising and appointing research studentships, and for overseeing their study. More information is provided in section (c).

Impact and Knowledge Exchange: See REF3a for information on the department's impact and knowledge exchange strategy.

The department's research strategy is linked to five-year activity plans that it is required to develop and maintain, in close consultation with the university. These plans relate to all aspects of the department's activities (including teaching, research, management, staffing, resources/finances,

and facilities and infrastructure). Plans are reviewed and updated annually as part of a comprehensive university-wide planning process.

INTELLECTUAL ENVIRONMENT: The department makes a substantial investment in its intellectual environment, illustrated by its rich collection of seminar programmes. As well as a departmental seminar series (weekly during term time), the Strachey Lecture series provides major set-piece occasions to hear from the world's leading computer scientists. Held three times per annum, Strachey lecturers during the REF2014 period have included Andrew Yao (Tsinghua), Mooly Sagiv (Tel Aviv), Christos Papadimitriou (Berkeley), Rajeev Alur (Pennsylvania), Robert E. Tarjan (Princeton), Linda Northrop (CMU), Anthony Finkelstein (UCL), Jane Hillston (Edinburgh), Orna Grumberg (TECHNION), Cliff Jones (Newcastle), Simon Peyton-Jones (Cambridge), Ed Clarke (CMU), Christopher Bishop (Microsoft), Randy Bryant (CMU), and Guy Steele (Sun Microsystems). In addition to these flagship programmes, regular seminar series are organised around all the department's research themes – departmental funds are provided to support these seminars (approximately £15K to £20K per annum). Visiting Professor Don Knuth (Stanford) and Emeritus Professor Sir Tony Hoare (Microsoft) each typically give at least one lecture per year.

RESEARCH STRATEGIES FOR INDIVIDUAL THEMES: Research in the department is currently focussed around seven overarching themes, as follows.

Algorithms *(Professors L. Goldberg, P. Goldberg, Gottlob, Jeavons, Koutsoupias, Ouaknine)*: The newly-established Algorithms theme deals with fundamental issues of computational complexity, including both (*i*) mapping the landscape of computational problems, determining which are tractable and which are intractable (quantifying the extent of tractability) and (*ii*) designing and analysing deterministic, randomised, and online algorithms for a range of problem domains. Future research will focus on:

Developing a comprehensive complexity theory of counting problems arising in a host of application areas including statistics, statistical physics, information theory, coding, and machine learning.

Designing and analysing centralised and distributed game-theoretic algorithms that run in systems controlled by many entities with different and sometimes conflicting objectives, such as the Internet.

Analysing the complexity of problems in logic, databases, and artificial intelligence, and in particular, constraint satisfaction, delimiting the tractability frontiers for such problems according to various relevant parameters, and designing algorithms that are efficient for large classes of instances.

Decision problems for linear dynamical systems including work on the Orbit problem and the positivity of linear recurrence sequences.

Automated Verification *(Professors Cardelli, Kroening, Kwiatkowska, Lowe, Melham, Ong, Ouaknine, Roscoe, and Worrell)*: The goals of this research are to develop theories, algorithms, implementation techniques, and software tools to ensure the correctness, reliability, security, and dependability of computer and software systems. Researchers in this theme have developed tools that are widely used in both research and applications: Casper (security protocol compiler), CBMC (model checker for ANSI C/C++), CProver (model checker for C), FDR (model checker), and PRISM (probabilistic model checker). Future research will focus on:

Foundational work on the algorithmic analysis and verification of infinite state, quantitative, and concurrent systems.

Developing quantitative models, abstraction-refinement, synthesis, and approximation techniques for complex and challenging real-world systems (e.g., next-generation concurrent systems, intelligent transport systems).

Scalable verification for DNA computing.

Automated verification of real-world, safety-critical timed systems, e.g., in the transport sector.

Computational Biology *(Professors Burrage and Gavaghan)*: The long-term goal of this highly interdisciplinary theme is to develop a rigorous theoretical and computational framework for problems at the interface between computational and life sciences. Future research will focus on:

Further development of our software tools for computational biology and physiology (e.g., Chaste: http://www.cs.ox.ac.uk/chaste/) to encompass a wider range of application domains.

Modelling the immune system; extending our translational work in computational modelling of the heart; extending our work in respiratory modelling to hyperpolarised gas imaging; and building upon a newly established collaboration in the area of verification, validation, and uncertainty quantification (VVUQ) with the Food and Drugs Administration in the US.

Foundations, Logic, and Structures *(Professors Abramsky, Coecke, and Ong)*: Includes research on quantum computation (high-level methods for quantum information and computation, based on new mathematical representations of quantum mechanics) and logic/semantics of computation. Future research will focus on:

Developing high-level methods for verifying quantum protocols; the analysis of multipartite entanglement; the analysis of non-locality and contextuality; the interactions between quantum correlations and causal structure; and the delineation of quantum mechanics in axiomatic, informational, and structural terms.

Extending applications of structural mathematical methods for representing processes, contextuality, and reflexivity to phenomena in physics, computation, game theory, economics, natural language, and cognition.

Higher-order model checking, combining ideas and methods from semantics with algorithmic techniques from automated verification and program analysis; game semantics and algorithmic applications; extraction of algorithms for program analysis; and connections with games from other branches of computer science and economics.

Information Systems *(Professors Benedikt, de Freitas, Gottlob, Horrocks, Lukasiewicz, Pulman, and Wooldridge)*: The long term goal of this broadly-based theme is the development of Intelligent Information Infrastructures – information systems that support rich and flexible data sources, are able to integrate information from heterogeneous sources, and can reason with large scale, incomplete, and semi-structured information sources. The theme encompasses research on description logics/ontologies, databases, machine learning, multi-agent systems, and natural language processing. Future research will focus on:

Databases, Ontologies, Description Logics: We will continue to be active in the development of ontology languages (e.g., OWL) and their applications, as well as the theoretical foundations of these languages (e.g., complexity and expressiveness of Description Logics). We will focus particularly on links with databases and query languages. In addition we will continue to develop the theory of hypertree decompositions as applied to knowledge representation languages, and the theory of semi-structured databases (XML, HTML).

Machine Learning: We will extend the theory and improve the methodology of Bayesian optimisation techniques for increased automation of large-scale systems, apply these techniques to develop new products in the areas of automatic machine learning, algorithm configuration, analytics, dynamic creative optimisation, control, and large-scale personalisation and recommendation, and develop polynomial time learning algorithms for practical Markov random field models in language, vision, and quantum annealing. In addition, we will develop Bayesian deep learning architectures for improved recognition with big data.

Multi-agent Systems: We will continue the computational analysis of cooperative games, including tractable representation schemes and efficient computation of solution concepts; develop techniques for automated equilibrium analysis of game-like multi-agent systems; and continue our study of knowledge representation for multi-agent systems.

Natural Language Processing: We will develop models of compositional semantics learnable from widely available data; develop machine translation models capable of handling the wide array

of language phenomena that cause failures in the current generation of translation systems; continue to develop algorithms that extend the depth and complexity of probabilistic graphical models, both directed and undirected, that underpin all our natural language processing systems.

Programming *(Professors Cardelli, Davies, Gibbons, de Moor)*: The goal of research in this theme is to enable both the better use of existing programming languages and the design and development of better languages in the future. Future research will focus on:

Richer type systems (e.g., dependent types) and more powerful parameterization techniques (generic programming), which promote flexibility without sacrificing precision.

Tools for lightweight construction of *domain-specific languages*, tailored for specific classes of problems.

Model-driven development, whereby high-level system specifications are automatically transformed into executable code or configurations for generic frameworks.

Security *(Professors Creese, Lowe, and Roscoe)*: The importance of IT security is self-evident, as is the fact that, since the potential sources of insecurity are so wide-ranging, we need to research diverse topics within security and have the vision to bring these together into an overall concept of systems security. Major milestones in the development of this theme over the REF period include: becoming an EPSRC-GCHQ Academic Centre of Excellence in Cyber Security Research; becoming a Capacity Building Centre for the FCO; and the recent award of a CDT in Cyber Security. Future research will focus on:

Cryptographic protocols, trusted computing, information flow, distributed databases and access control, human and sociological factors, wireless and ad-hoc security, cyber security (tools, attack models, etc.), and steganography.

The above seven themes represent the overwhelming bulk of research submitted under this UoA, although we also return a small number of individuals from other institutes at the University of Oxford:

The ***Oxford e-Research Centre*** (OeRC) was founded with the goal of providing computational support to research from disciplines beyond computer science and now engages in the transformation of digital scholarship across the whole academic spectrum, including physical sciences (e.g., energy, science data processing in the square kilometre array radio telescope), social sciences (e.g., web observatories, social machines), digital humanities (e.g., computational musicology), and the medical sciences (e.g., biosharing), as well as in software sustainability. The research mission of OeRC is to develop innovative technology that will transform research, especially where society engages with computational capability. OeRC has active collaborations with the Department of Computer Science in areas such as cyber security, semantic web applications, and responsible innovation.

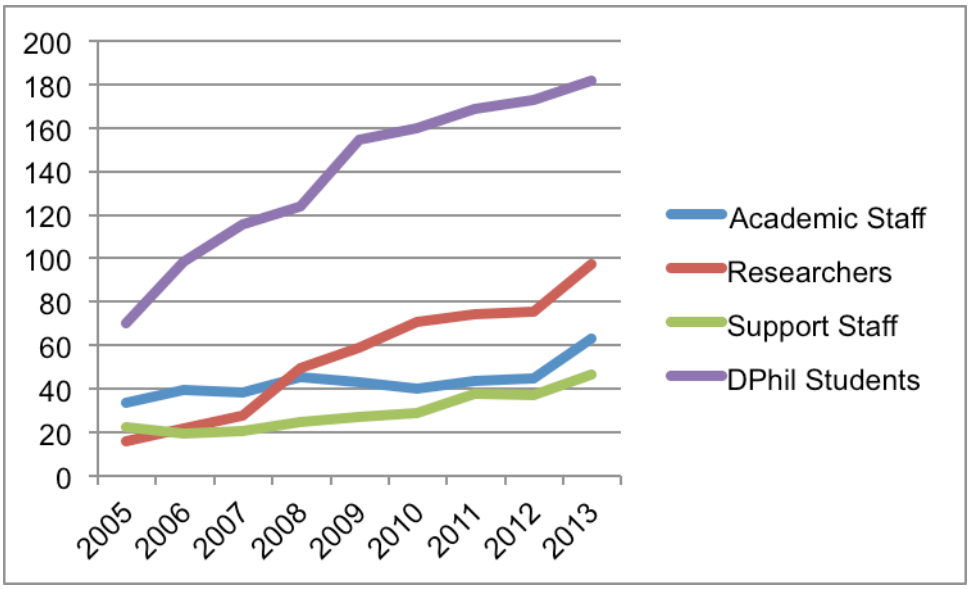
The ***Oxford Internet Institute*** (OII) is based in the university's Social Sciences Division, and carries out research into the societal implications of the Internet.

EVALUATION OF CURRENT POSITION WITH RESPECT TO RAE2008: Key objectives for the department following RAE2008 were: (*i*) to widen our research portfolio, with the goal of becoming a broadly based computer science department, carrying out research spanning the whole spectrum of computer science, from pure theory to deployed applications; (*ii*) to increase the research funding base and widen the range of research funders; (*iii*) to increase DPhil student numbers; and (*iv*) to enhance the infrastructure for computer science at the University of Oxford, both in terms of administrative support for researchers and facilities for carrying out research.

Tremendous progress has been made in each of these objectives: (*i*) since RAE2008, the department has opened up two major new research themes (Security and Algorithms) and has significantly expanded its AI and machine learning research areas, supported by a total of 27 new academic appointments and many fellowships; (*ii*) research grant expenditure per annum is currently nearly *six times* our average for RAE2008; (*iii*) we are currently graduating on average

more than twice as many DPhil students per annum compared to RAE2008; and (*iv*) we currently employ approximately 20 more support staff than at the time of RAE2008, and have taken occupation of a building refurbished specifically for us.

The following graph illustrates the dramatic growth of the department since 2005 (*y* axis shows headcount).



(c) People

STAFFING STRATEGY AND STAFF DEVELOPMENT: The key principles of the department's staffing strategy are: (*i*) the appointment of genuinely world-class academics, with academic appointments at all levels required to demonstrate international leadership in their area; (*ii*) the goal of ensuring that all research themes are supported by staff at a range of levels of seniority and experience, in order that staff are provided with the research leadership and support to enable them to achieve their full potential; and (*iii*) the need to continually review, renew, and refresh research themes. In pursuit of this strategy, we have made a range of excellent new appointments both at senior level (Professors Luca Cardelli [Programming, Verification], Min Chen [OeRC], Sadie Creese [Cyber Security], Nando de Freitas [AI], Leslie Goldberg [Algorithms], Paul Goldberg [Algorithms], Elias Koutsoupias [Algorithms], David de Roure [OeRC], and Michael Wooldridge [AI]) and lecturer level (Abate, Barrett, Blunsom, Cremers, Cuenca-Grau, Elkind, Forejt, Goldsmith, Kiefer, Krotsch, Lukasiewicz [now Professor], Markham, Martinovic, Minary, Nikitina, Rasmussen, Yang, and Zivny). The department's staffing strategy has benefited greatly from Oxford University's decentralised resourcing model, enabling us to respond rapidly to opportunities such as hiring promising researchers and establishing new research themes and groups. In addition, it has enabled us to offer flexible employment mechanisms, such as research fellowships for promising DPhil students and postdoctoral research staff, enabling them to establish or consolidate independent research careers. Three staff returned here are currently supported by such department-funded fellowships: Kharmalov, Pasechnik, and Vicary.

Support for New Staff: All new junior academic staff are assigned a mentor, who provides confidential support for all aspects of the academic role, such as advice and guidance on the establishment and maintenance of a research programme, workload management, grant proposal writing, and lecturing and tutoring. Junior academic staff are appointed initially for a five year probationary period, and throughout this period the mentor is required to encourage and monitor attendance at appropriate university training courses, and provides a written report to a review panel at the conclusion of this probationary period. New staff have substantially reduced teaching loads in their first three years of employment (at the rate of 0.5, 0.67, and 0.83 of normal loads), giving them the space to consolidate their independent research career. Funds are available to support equipment and travel for all academic staff and students – e.g., approximately £40K per

annum is allocated for conference travel support. Academic staff are given significant support with respect to planning for research funding and for post-award grant management (see section (d) of this document).

Support for Established Staff: The University of Oxford recognises the challenges that arise in maintaining a high level of research activity throughout an entire career, and provides mechanisms that enable staff to maintain research productivity and focus. The key mechanism is the university's well-established, generous, and rigorously implemented sabbatical programme, through which all academic staff are entitled to one term sabbatical leave for every six terms worked. Staff are fully funded during sabbaticals, and research funding for sabbatical leave (e.g., travel) is provided both by the department and also by Oxford's colleges. Mentoring is provided to staff well in advance of sabbatical leave, to enable them to develop realistic and productive research plans and make the best use of their study leave.

Concordat to Support the Career Development of Researchers: Oxford University has enthusiastically endorsed the principles of the Concordat, and has implemented them through its own *Code of Practice for the Employment and Career Development of Research Staff*. This Code of Practice maps the Concordat into the university's own organisational context (e.g., considering the role of colleges and the highly decentralised organisational structure of the university). All departments within the university are required to embed the Code of Practice into the operational running of the department. Support for implementing the Code of Practice is provided by the Oxford Learning Institute (focussing on personal and professional developmental issues), Personnel Services (HR issues), Research Services (research grants, ethical issues, and research integrity), the Equality and Diversity Unit, and the Careers Service. Evidence of the success in supporting and developing research staff is provided by the fact that the university has gained the European Commission's HR Excellence in Research Award, which recognises the systems and practices the university has in place to support the careers of researchers and encourage their professional development in line with the Concordat.

Personal Research Fellowships Won in Open Competition: The department provides mentoring and academic guidance for writing fellowship proposals and carries out mock interviews for all shortlisted applicants. The success of this strategy is evidenced by the number of competitive fellowships awarded in the REF2014 period: five ERC Advanced Investigator Grants (L. Goldberg, Gottlob, Koutsoupias, Kwiatkowska, Wooldridge), five EPSRC Leadership/Career Acceleration fellowships or equivalent (Blunsom, Motik, Ouaknine, Sadrzadeh, Smith), three Royal Society University Research Fellowships (Cuenca-Grau, Kiefer, Zivny), nine EPSRC Post-Doctoral Fellowships, and a host of others.

International Staff Appointments: The University of Oxford is committed to hiring only the very best academic staff, irrespective of nationality or racial origin. The success of this policy is evidenced by the highly diverse nature of the staff returned under this UoA. Of the staff we return here, 47 are of overseas origin: Australia (2); Austria (2); Belgium (1); Canada (2); China (1); Croatia (2); Czech Republic (2); Denmark (1); Estonia (1); Germany (8); Greece (2); Hungary (1); Italy (4); Korea (1); the Netherlands (3); New Zealand (1); Poland (1); Portugal (1); Romania (2); Russia (2); Singapore (1); Spain (2); USA (3); and Zimbabwe (1). The roster of research staff and PGR students similarly reflects this diversity.

Training for Postdoctoral Researchers: Divisional Skills Training (Postdoctoral Researchers) offers a programme of generic skills training tailored for postdoctoral researchers aimed at supporting them at various stages of their research and providing support for their professional development and future careers. Example courses include "Building a Successful Career in the Sciences", "Personal Effectiveness", and "Career Management".

Support for Equality and Diversity: The university received a Bronze award under the Athena SWAN scheme in 2010. The department provides funding for a Computer Science Women's Group, which has also been supported by external funding from Google. The Women's Group provides both pastoral support and more formal career guidance for women in the department at all stages of their academic career. The Women's Group organise social events, networking meetings, and a distinguished speaker series. In addition, the Oxford Women's Network (OWN) is

a university-run service that provides women working at all levels in the collegiate university with support services, giving practical advice and guidance on all aspects of their career. Finally, in July 2013, the university established the Vice-Chancellor's Diversity Fund, providing £1M as a resource for the advancement of diversity at the University of Oxford amongst academic and research staff.

POSTGRADUATE RESEARCH (PGR) STUDENTS: The past decade has witnessed a steady and continuing expansion in PGR student numbers in the department.

PGR Funding: The biggest increase in PGR student numbers has arisen from our involvement in EPSRC-funded Doctoral Training Centres (now called Centres for Doctoral Training – CDTs). This activity is currently focussed largely around the Life Sciences Interface (about £13M funding total), Systems Biology (£9M), and Systems Approaches to Biomedical Science (£6.6M). More than 300 students have been enrolled in these programmes to date, with about 40 students enrolling each year. The programmes enjoy collaborations with a range of other Oxford University departments (e.g., Zoology, Mathematics, Biochemistry) and have 14 partner companies in the UK. An EPSRC-funded CDT in the area of Cyber Security was awarded in 2013 (£3.75M).

PGR Admissions: The baseline expectation for admission to the department's DPhil programme is a first-class degree in a 4-year programme in computer science or a cognate discipline. Suitably qualified applicants for the DPhil programme are required to write an outline research proposal, and are interviewed by at least two academics with expertise in the proposed research area.

PGR Progress Monitoring: In their first year of study, DPhil students are initially registered as "Probationer Research Students". Throughout their study, graduate students are expected to contribute to the termly Graduate Supervision System, which enables students to record training they have received and document progress they have made. Supervisors are required to write a report on progress, which is then considered by the Director of Graduate Studies and college advisors. At the end of their first year, DPhil students are required to apply for transfer to DPhil status. The transfer of status requires the submission of a portfolio of courses attended and other training, three pieces of assessed work, and a qualifying dissertation. These are evaluated by two examiners. In the second and third years of study, students are formally monitored through termly reports, and towards the end of their third year, students are evaluated with respect to whether they are on track to submit a successful DPhil thesis. This evaluation involves both a viva and written component. University regulations require that students must successfully complete this evaluation before submitting a thesis.

Academic Support for PGR Students: A programme of generic skills training is provided by the university, intended to underpin PGRs' research activities (e.g., "Finish Your DPhil", "Research Integrity", and "Academic English"), and to enhance career development skills. In addition, the *Graduate Academic Programme* brings together all the training available in departments in the MPLS Division (of which Computer Science is a part), and makes it available to all graduate research students in the division. This means graduate research students have access to approximately 350 courses including academic courses, research, teaching, transferable skills, and career development training. The department's CDTs provide many specialised courses for PGR students – more than 60 in total for the life sciences CDTs alone. In addition, the CDTs have dedicated teaching facilities in the department for the Cyber Security CDT, while a separate facility provides specialised teaching facilities for the life sciences (comprising two 60 seat lecture theatres, 20 seat meeting rooms, and PGR student office accommodation).

(d) Income, Infrastructure, and Facilities

Research Income: The department has seen a huge and sustained increase in grant income since RAE2008. For the REF2014 period we report a research grant expenditure of £52.2M (up from £9.5M in RAE2008). At present, we hold approximately 130 research grants. We have a proactive research facilitation scheme, which commences with the induction of new academics to the research funding environment and the facilities provided to support the grant application process. The department funds two full-time grant support officers for pre-award support, providing grant costings and advice on financial and legal aspects of grant proposals. A further three full-time

post-award grant support officers are also funded by the department, responsible for processing financial transactions on grants, preparing financial reports for grants, etc. To provide support for specific large grants, the department funds a further 2.5 FTE grant officers. The university's Research Services office handles all bids for external research funding. The success of the department's research income strategy is evidenced by the fact that, over the REF period, our overall success rate for grant applications has averaged 40% of applications funded by number, and 31% by value. In terms of RCUK grant applications, our success rate has averaged 44% by value over the REF2014 assessment period.

The department also receives valuable research support from Oxford's colleges. Many colleges provide "Junior Research Fellowships" (fully-funded research fellowships for junior researchers, roughly equivalent to EPSRC post-doctoral research fellowships). In addition, colleges also provide financial support (e.g., funds for travel and minor items of equipment) and academic support for research students and fellows. More generally, the department has been financially successful throughout the REF2014 assessment period, with a total net surplus of £5M over the financial years 2008-2013. This success is in part due to the dramatic increase in research income that we have witnessed, and in addition, to the success of our Software Engineering Programme. This financial success has enabled the huge investment in new academic staff described in section (c) of this document, and has allowed us to make substantial investments in buildings and facilities, as detailed below.

Buildings & Estates: The department's buildings comprise approximately 9000 square metres of space, over three locations in central Oxford. The main site houses some 190 staff and 120 DPhil students, who are provided with office space and central facilities (e.g., secretarial support, common room facilities, computing support). In addition, the department hosts approximately 40 academic visitors at any given time, as well as 320 part-time MSc students and 70 full-time MSc students, and a vibrant undergraduate community. Our buildings also provide teaching, research, and library facilities. Our total staff head count has approximately doubled over the past six years, requiring expansion into two annex buildings. A recently completed £600K refurbishment of the Robert Hooke Building has created additional office space, high-quality seminar rooms, a designated Cyber Security Centre, an exhibition/demonstration capability, and rooms for the newly funded Centre for Doctoral Training in Cyber Security.

Library Provision: The department has a long-established internal research library, which provides a comprehensive collection of research reference works, key journals in print form, past DPhil theses, technical reports, and key computer science book series (e.g., Springer LNCS). The library is staffed by two librarians. We also benefit from the university's world-class Bodleian Libraries; in particular, the Radcliffe Science Library (which provides support to this UoA) has more than a million volumes of printed materials, with over 120,000 books and 1,400 print journals available on open shelves. The Radcliffe Science Library provides complete electronic access to journals from professional societies including ACM, IEEE, SIAM, AMS, and all major publishers. Conference proceedings from key societies and publishers are also taken in toto (e.g., Springer LNCS, IEEEXplore).

Research Facilities: Much of our research requires no specialised laboratory facilities, and no computing facilities over and above ordinary desktop computers. Most researchers are therefore office-based. Of those researchers that do require specialised facilities (notably the Computational Biology theme), the main requirement is for super computing facilities, and for them, the university's Advanced Research Computing (ARC) centre is the key resource. It has three large general-purpose clusters, ARCUS (1344 cores), SAL (640 cores) and HAL (512 cores), and a number of smaller clusters offering specialised facilities, such as shared memory HPC (CARIBOU, 1TB) and GPU-based HPC (SKYNET, 16 CPUs and JADE, 12 GPUs). The university is a consortium member of two regional infrastructures, IRIDIS (12,000 cores) and EMERALD (372 NVIDIA Tesla processors, 114TF). EMERALD is currently one of the largest GPU clusters in Europe. During the census period, OeRC hosted major infrastructures for the UK National Grid Service, including some 25% of production service hardware and 50% of their cloud services. OeRC is currently leading the development and deployment of Europe's next generation e-infrastructure through the European Grid Infrastructure Federated Cloud Task Force. ARC and

OeRC provide expertise to support the development of effective highly parallel programs to fully exploit the power of the clusters, as well as specialised software tools/libraries for high performance scientific applications.

Support for Technology Transfer: Extensive support is available to all staff to facilitate technology transfer and promote the wider impact of their research. Isis Innovation Ltd, a wholly owned subsidiary of the university, is the main vehicle through which this support is provided. Full details are provided in our impact statement (REF3a).

Consulting & Professional Services: All academic staff at the University of Oxford are encouraged to undertake consulting, and are permitted to undertake paid consulting contracts up to 30 days per annum without loss of salary (more by individual arrangement). Oxford University Consulting (a wholly-owned subsidiary of Isis Innovation, the university's knowledge exchange company – see REF3a) provides a professional framework within which staff can undertake such consulting, handling both legal and administrative aspects (e.g., contracts, insurance, invoicing), as well as providing a single point of contact for third parties looking for specific expertise. During the REF2014 period, Oxford University Consulting handled consulting contracts for staff returned in this UoA in areas as diverse as ontology querying, sentiment analysis, and energy management systems.

(e) Collaboration and Contribution to the Discipline or Research Base

MAJOR RESEARCH COLLABORATIONS: This UoA has supported a huge range of research collaborations throughout the REF period, both with organisations (through joint projects and funded research) and with individuals (typically on specific research topics). Examples of organisations that have funded research projects in this UoA during the REF2014 include: Alcatel Lucent; Fujitsu; GlaxoSmithKline; Google; Intel Corporation; Microsoft; QinetiQ Ltd; Siemens AG; and Toyota. The total direct support from such organisations in the REF2014 period amounts to approximately £3M.

In terms of individual research collaborations, staff have one-to-one research collaborations with many of the world's leading researchers – key collaborators in the REF2014 period include:

Algorithms – Bulatov (Simon Fraser), Deng (Liverpool/Hong Kong), Grohe (RWTH Aachen), Jerrum (QMUL), Kearns (Pennsylvania), Papadimitriou (Berkeley), Voecking (RWTH Aachen).

Automated Verification – Clarke (CMU), Cook (Microsoft Research), Etessami (Edinburgh), Ghezzi (Politecnico Milano), Grundy (Intel), Hu (UBC), Malik (Princeton), Phillips (Microsoft Research), Rabinovich (Tel Aviv), Schnoebelen (ENS Cachan), Vardi (Rice).

Computational Biology – Abi-Nerges (AstraZeneca), Bond (Monash), Chiu (Baylor), Coveney (UCL), Efimov (Washington St. Louis), Emmott (Microsoft Research), Gray (US Food and Drug Administration), Hunter (Oxford Cardiology), Kohl (Imperial), Kornberg (Stanford), Varro (Szeged), Wild (Sheffield).

Foundations, Logic, and Structures – van Benthem (Amsterdam), Bundy (Edinburgh), Clark (Cambridge), Hardy and Spekkens (Perimeter Institute for Theoretical Physics, Canada), Brandenburger (New York University), Vaananen (Helsinki), and Ying (UTS/Tsinghua).

Information Systems – Abiteboul (INRIA/College de France), Bilmes (Washington), Dyer (Carnegie Mellon), Eiter (TU Vienna), Esposito (Bari), Fridrich (SUNY Binghamton), Koch (Cornell/EPFL), Kifer (Stony Brook), Kolaitis (California Santa Cruz), Kraus (Bar-Ilan), Lang (Paris Dauphine), Lopez (John Hopkins), Mihalcea (Texas), Segoufin (INRIA), Tennenholtz (Technion), Valiant (Berkeley), Wolter (Liverpool).

Programming – Birkedahl (Aarhus), Cook (Microsoft Research), Henglein (Copenhagen), Hu (National Institute of Informatics Japan), Kobayashi (Tokyo), O'Hearn (UCL/Facebook), Pierce (Pennsylvania), Rutten (CWI, Netherlands), Sagiv (Tel Aviv).

Security – Black (Dundee), Brock (Draper Labs), Lamberts (Warwick), Lee (Princeton), and Tsudik

(Berkeley).

CONTRIBUTION TO THE RESEARCH BASE: Staff in this UoA have been enormously active in contributing to their respective research areas, not just with regard to research results, but also with respect to the development of research-oriented software tools, international standards, problems, and datasets. Notable examples include:

- The work of the Computational Biology theme on the CellML standard for the definition and exchange of computer processable models, particularly in the biology domain (http://www.cellml.org/).
- The work of the Automated Verification theme on model checking tools for formal automated verification, such as PRISM (http://www.prismmodelchecker.org/) and the CBMC system for model checking ANSI C/C++ programs (http://www.cprover.org/cbmc/).
- The work of OeRC on supporting the Oxford Text Archive and British National Corpus, fundamental research facilities for English language and computational linguistics research (http://www.natcorp.ox.ac.uk/).
- The work of the Information Systems theme with the World-Wide Web Consortium on the OWL 2 Web Ontology Language (http://www.w3.org/TR/owl2-overview/) and the development of various ontology reasoning systems such as ELK (http://code.google.com/p/elk-reasoner/).

Each of these represents a major research contribution in its own right, but has also provided a framework upon which others have carried out substantive research.

Staff in this UoA have organised a rich and diverse range of conferences in Oxford during the assessment period, and for this purpose were able to take advantage of Oxford's colleges, many of which provide accommodation and meeting facilities in venues that are modestly priced and highly attractive for participants. Examples of conferences we have organised include: 29th British National Conference on Databases (BNCOD-2013); 14th Towards Autonomous Robotic Systems Conference (TAROS-13); 24th Symposium on Implementation and Application of Functional Languages (IFL-2012); Quantum Information Sciences Workshop (QISW-2012); 19th International SPIN Workshop on Model Checking of Software (SPIN-2012); 17th IEEE International Conference on Engineering of Computer Based Systems (ECBS-2010); 15th IEEE International Conference on Engineering of Complex Computer Systems (ICECCS-2010); 22nd International Workshop on Description Logics (DL-2009); 3rd International Conference on Geosensor Networks (GSN-2009); 25th Conference on the Mathematical Foundations of Programming Semantics (MFPS-2009).

INTERDISCIPLINARY RESEARCH: This UoA has extremely strong interdisciplinary links, both with other departments at the University of Oxford and beyond. For example:

- We work with ***Biology, Mathematics, and Medicine*** through the Computational Biology theme and Software Engineering programme. For example, Professor Jim Davies is Director of the Oxford NIHR Biomedical Research Centre (BRC) Informatics Programme, leading the development of the data architecture for Genomics England Ltd, the UK Government Department of Health company that is responsible for the UK 100,000 genome project.
- We work with ***Economics and Finance*** through the Oxford-Man Institute of Quantitative Finance (http://www.oxford-man.ox.ac.uk/). Founded in 2007 and with substantial seed funding from Man Group PLC, the Oxford-Man Institute brings together researchers from across the University of Oxford who carry out research relating to quantitative finance: of relevance to this UoA is work on computational finance (Professor Gottlob, a founding fellow of the Institute) and agent-based modelling (Professor Wooldridge).
- Links with ***Physics*** are provided through work on quantum structures in the Foundations theme (e.g., collaborating with Oxford-based physicists through the "Qubit" quantum computation research group within the Department of Physics: http://oxfordquantum.org/).
- OeRC provides strong links to the ***physical sciences*** (e.g., through the provision of supercomputing facilities and support for these), and leads the e-Research South Regional e-Science Consortium; and with the ***humanities*** through the Digital Humanities programme

(http://digital.humanities.ox.ac.uk/). OeRC increasingly engages with disciplines across the whole academic spectrum.

- Finally, links with the ***Social Sciences Division*** are provided through the Oxford Internet Institute, which is focussed on social and philosophical implications of the Internet.

EXEMPLARS OF RESEARCH LEADERSHIP:

Fellowships of Learned Societies: Chen – Fellow of EuroVis; De Freitas – Fellow of the Canadian Institute for Advance Research (CIFAR); Gottlob – Fellow of the Royal Society (FRS) 2010; Horrocks – Fellow of the Royal Society (FRS) 2011, Fellow of Academia Europaea 2012, Fellow of European Coordinating Committee for Artificial Intelligence (ECCAI) 2009; Kwiatkowska – Fellow of Academia Europaea 2012; Roscoe – Fellow of Royal Academy of Engineering (FREng) 2011, Fellow of Academia Europaea 2011; Wooldridge – Fellow of Association for the Advancement of Artificial Intelligence (AAAI) 2008.

Selected Scientific Leadership Roles: Gibbons – Vice-Chair ACM SIGPLAN; Ong – General Chair, ACM/IEEE Symposium on Logic in Computer Science (LICS); Wooldridge – President International Foundation for Autonomous Agents and Multi-Agent Systems (IFAAMAS).

Selected Research Awards and Prizes: Abramsky – BCS Lovelace Medal 2013; Creese – IBM Faculty Award 2009; P. Goldberg – 2008 Game Theory and Computer Science Prize, 2011 SIAM Outstanding Paper Prize; Gottlob – Royal Society Wolfson Research Merit Award, and Alberto O. Mendelzon Test-of Time Award; Horrocks – Semantic Web Science Association Ten-Year Award 2013; Koutsoupias – 2011 ACM SIGACT/EATCS Gödel Prize; Kröning – Haifa Verification Award 2011, and Royal Society Wolfson Research Merit Award 2013; Lukasiewicz – AI Journal Prominent Paper award 2013; Motik – BCS Roger Needham Award 2013; Ouaknine – BCS Roger Needham Award 2010; Turilli – Brian Michael Goldberg Memorial Award.

Best Paper Prizes: Chen et al – EuroVis-2008; De Freitas *et al* – IJCAI-2013; L. Goldberg *et al* – ICALP-2012 (Track A); L. Goldberg *et al* – ICALP-2010 (Track A); P. Goldberg *et al* – ACM EC-2008; Gottlob *et al* – CP-2011; Gottlob *et al* – PODS-2009; Grau *et al* – AAAI-2010; Jeavons *et al* – ECAI-2008; Ouaknine *et al* – CONCUR-2011; Wooldridge *et al* – AAMAS-2011; Wooldridge *et al* – AAMAS-2009; Wooldridge *et al* – AAMAS-2008; Yang *et al* – CONCUR-2012.

Membership of Major Scientific Committees: Abramsky – LICS Advisory Board member; Creese – Strategic Advisory Committee, RCUK Global Uncertainties Programme; Gottlob – Board Member Informatics Europe, Member Royal Society Election Panel 1 (Mathematics & Computer Science), ACM Grace Murray Hopper Award Committee member; Kwiatkowska – Member REF 2014 Subpanel 11, and Chair ERC Starting Grants Panel (2012, 2014); Melham – EPSRC Strategic Advisory Network.

Chairing of Major International Conferences: Benedikt – PC Chair PODS 2012; De Freitas – PC Chair UAI-2012, General Chair UAI-2013; Goldberg – ICALP-2008 (Track A); Gottlob – General Chair BNCOD-13, 2013, PC Chair, SOFSEM-2012; Kwiatkowska – PC Chair, ICALP-2013 (Track B); Ong – PC Chair FoSSaCS-2010; Ouaknine – PC Chair MFPS-2011; Wooldridge – PC Chair ECAI-2010; Yang – PC Chair APLAS 2011.

Selected Invited Talks at Major International Conferences/Named Lectures: Abramsky – The Uncomputable 2012, Milner Symposium 2012; Gottlob – MFCS-2012, ETAPS-2012, STACS-2011, ETAPS-2012, ICDE-2011, ICLP-2011, ISAIM-2010, ICALP-2009, ICDT-2009; Horrocks – ECAI-2010, ICDT-2010, KR-2010; Kwiatkowska – 2012 Milner Lecture, University of Edinburgh; Ong – ETAPS-2008, MFPS-2012; Ouaknine – ICALP-2010; Wooldridge – ECAI-2012.