Institution: The University of Leeds

Unit of Assessment: 11 (Computer Science and Informatics)

a. Overview

This UoA is coincident with the School of Computing (SoC) within the Faculty of Engineering at Leeds (UoL). Our research is organised into five themes that reflect our distinctive approaches to computational thinking: **Algorithms and Complexity** (AC), **Distributed Systems and Services** (DSS), **Artificial Intelligence** (AI), **Computational Science and Engineering** (CSE) and **Applied Computing in Biology, Medicine and Health** (BMH). Since 2008 we have enhanced our international standing, growing the quantity and impact of our research in each theme. E.g.: **AC:** World-class contributions in theoretical computer science, from graph theory and optimisation to computational logic, including ground-breaking results on the complexity of the counting constraint, leading to Dyer's prestigious EATCS award. **DSS:** Fundamental insight into cloud operations and software solutions, supported by extensive collaborative grants and industrial partnerships, leading to commercialisation and international recognition, from paper prizes to Xu's IEEE Service Award. **AI:** Internationally leading contributions in activity analysis of complex, dynamic scenes, natural language analysis, highly downloaded open source tools for ontology creation, with prize winning data integration research (IET Innovation Award) and Cohn's AAAI Distinguished Service Award. **CSE:** The cracking of the major long-standing problem holding back multi-field analysis opened new territory for multi-variate 'big data' visual-analytics, leading to important discoveries in physics. **BMH:** Our methods for integrated systems thinking led to a series of foundational insights on the role of physics in biological computation, while collaborations with AI, CSE, NHS and international partners led to innovative solutions for medical data analysis, from neurology to histopathology.

b. Research strategy

O*ur vision* is to *deliver wide reaching, significant impact and international excellence in applied and interdisciplinary research based upon an outstanding core of fundamental computer science*.

The broadening of our research structures to two Institutes (Artificial Intelligence & Biological Systems; Computational & Systems Science), laid out in our RAE'08 plans, has facilitated greater cross-pollination, which we have since cemented into the five research themes, reflecting the areas in which the School excels, has critical mass, and that are aligned with our vision and strategies for the future (details under individual themes). To promote interaction and collaboration, members of staff are affiliated with any number of themes, each of which runs its own research seminars, specially-tailored postgraduate training, etc. Strategic plans achieved within the REF period include (i) maintaining our excellence in core areas of computer science, in every theme; (ii) strengthening links across research areas; and (iii) being a major driver of leading interdisciplinary research, and, in the process, informing and enhancing 'computational thinking' across the University and beyond.

Our distinctive core and collaborative approaches (e.g. vision & logic in AI, topology & systems in CSE, AC & DSS, etc.) are manifest in outstanding achievements across the board (see highlights below). This excellence is underpinned by increased and diversified research income from £8m in RAE 2008 to £12.1m in REF14 (including 6 UKRCs, TSB/DTI, DARPA, ARC, EU, Wellcome Trust, industry and more), supporting our vibrant body of research staff and students, with about 80 RAs employed by the School since 2008 and a current cohort of 20 RAs and 50 PhD students (see Part d). **Strategic plans and achievements for each of our research themes** are summarised below.

Algorithms and Complexity (AC) (Beyersdorff, Dyer, Muller, Shakhlevich, Vušković)

Leeds is internationally renowned for research in graph theory, combinatorics and optimisation. As part of our outward looking strategy, we have expanded our already strong network of collaborations to further international leaders and joined forces with other domains and application-driven research, from computational logic to grid and operational research. Achievements include:

- Dyer's work on the **counting constraint satisfaction problem** led to his prestigious EATCS award (2013). E.g. [Dyer3] completely settled a fifteen-year old dichotomy conjecture. Vušković [1-4] and Muller [2,4] gained new insights into the use of **decomposition methods** for the study of hereditary graph classes, producing important structural results with algorithmic consequences. Collaborations (EP/K016423/1) include Nicolas Trotignon (Ecole Normale Superieure, Lyon) and Maria Chudnovsky (Columbia University), winner of the Fulkerson Prize and MacArthur Fellow.
- Beyersdorff broadened our research to **computational logic.** His work on the complexity of

satisfiability problems, both for classical and non-classical (temporal and non-monotonic) logics led to efficient algorithms in a parameterised context [4] and complexity barrier analysis, e.g. for Theorem Proving [3,4] and proof verification [1-3] (funding, John Templeton Foundation).

- Shakhlevich's research spans the theoretical and the applied, from foundational contributions to scheduling with controllable parameters (EP/J019755/1) and inverse scheduling (EP/D059518/1) to grid scheduling (EP/G054304/1). Her work on patient scheduling (with NHS partners) opened up a new direction of theoretical research – scheduling resource and job patterns (EP/K041274/1).

Motivated by ever-growing challenges around 'big data', we will continue our multi-pronged approaches, advancing foundations of complexity and graph theory, logic and optimisation and their applications, from security to cloud. In so doing we will: strengthen links with AI (Cohn) around computational logic; build on momentum with the School of Maths (our Algebra, Logic & Algorithms seminars, joint PGR training); and enhance links with DSS, BMH and growing industrial partners.

Distributed Systems and Services (DSS) (Dimitrova, Djemame, Jimack, Lau, Shakhlevich, Xu)

World leading research in DSS is two-pronged: pushing our scientific understanding of distributed systems (both physical and human factors) while applying this knowledge in systems engineering and across domains through industrial, government and NHS partnerships. Achievements include:

- Four award winning publications and significant impact to industry (Part e and REF3a) arose from research in **grid/cloud computing** with focus on dynamic, dependable service provision [Xu2; Djemame1-4], security [Xu1] and implications for energy efficiency [Xu4]. Support included ESRC, EPSRC, EU, TSB (£3.4m to Leeds) and Chinese grants (~£3.35m from the Chinese NSF and National Key Laboratory). E.g. Xu's CROWN-C grid middleware system (IEEE Computer 41, 2008+ [Xu1]) is an output of our collaboration with Beihang (EP/D077249/1, EP/F057644/1) solving multiple open dependability challenges. AssessGrid delivered the first risk-aware grid broker [Djemame3]. In OPTIMIS, we delivered cloud system architectures to support federated, multi-cloud and brokerage scenarios, central to next generation cloud service ecosystems [Djemame4].
- Working in major multidisciplinary collaborations, we delivered **data/knowledge management** tools and systems, including the innovative GENESIS system for social science data management (£2.4m, £300k to Leeds), a semantic-driven conceptual architecture for atmospheric science [Lau3], and semantic architectures for growing semantic spaces (Linked Data, EU Dicode) [Lau4] and for social media (EU ImREAL) [Lau1,2], the latter in collaboration with AI.

Looking forward, we will continue to develop capability in: (i) energy-efficient cloud data centres, building on Djemame's €3.1m ASCETiC (Leeds £500k, 2013-16) and Xu's award winning work on Google data [Xu3]; (ii) advanced systems engineering (building on £1.37m TSB STRAPP project 1926-19253) with Rolls-Royce, Cybula, and Xu's new partnership with Jaguar Land Rover (Leeds: £750k EP/K014226/1) & (iii) large & secure data systems (building on GENESIS; see also BMH).

Artificial Intelligence (AI) (Atwell, Beyersdorff, Bulpitt, Cohen, Cohn, Dimitrova, Hogg, Lau, Magee, Markert, Michael, and until recently Everingham, deceased)

Leeds uniquely exploits synergies between different modalities of AI. World leading contributions from this strategy, supported by >£4m from government, EU and industry, are fertilised by close collaborations with end-users and other disciplines, from religious studies (EP/K015206/1 and [Atwell3]) to engineering (MTU, NeTTUN) (see also BMH, DSS & REF3a). Achievements include:

- Our >20 year international leadership in **qualitative spatial calculi** includes fundamentals (e.g. [Cohn3,4] COSIT-11 best paper; Australian Research Council grant partner) and applications, attracting world leading visitors (see Part e and [Michael1-4]). Mapping the Underworld (MTU, ~£1.7m) has delivered the world's first integrated utility data [Cohn2] across Scotland (REF3a). A new €10m EU grant on tunnelling (Leeds:€860k) builds on MTU and ontology modelling [Dimitrova1]. Further data fusion work is detecting archaeological residues through **remote sensing** (AH/H032673/1) with anticipated impact on land management and development control.
- Three major collaborative EU projects (two Leeds led, €2.1m to Leeds) led to fundamental research and industry-ready tools to augment *individual* [Dimitrova1,4] and *collective* [Dimitrova2,3] human intellect, including **intelligent support** for learning, knowledge creation, sense-making and decision making; all use our open source ontology creation tool ROO [Dimitrova2] (Part e, REF3a).
- Our distinctive combination of computer vision with knowledge representation has made us an international leader in **Activity Analysis** [Hogg1,3,4; Cohn1,3], with many keynotes (e.g. KR14, ICAPS12). Major funding (£2.9m: EPSRC, EU, SRI subcontractor in DARPA Mind's Eye program)

led to the first successful learning of qualitative relational models from real world video (supervised [Hogg1] and unsupervised [Cohn1]). **Image segmentation** research spans fundamentals [Hogg2; Magee3] & applications, e.g., design [Hogg2], performing arts, sports (Prozone Case Studentship), medicine (see BMH & REF3a for [Magee1-4; Bulpitt4] and several commercialisations thereof).

- Our **NLP** research includes an especially strong multi-lingual focus, delivering high-performing algorithms for important language phenomena [Markert3,4] and resources for academics and the general public [Markert1,3; Atwell1,3,4], with applications ranging from anaphora resolution [Markert4] to neuroscience (see [Market2] in BMH). [Atwell3] presents one of the highest-impact resources for Arabic, used by religious scholars, linguists and the general public (>1 million visits).

Looking forward, we will continue to chart new territory integrating learning, reasoning, language, and personalisation. In robotics, we will link activity analysis ([Cohn1; Hogg1,3,4], EU STRANDS, RACE), with insight from animal behaviour ([Cohen3,4], EP/J004057/1) to deliver robust, adaptive autonomous systems, capitalising on our new £4.3m EPSRC National Facility for Innovative Robotic Systems and leading role in the Leeds Centre for Mechatronics and Robotics (see Part d).

Computational Science and Engineering (CSE) (Bollada, Carr, Cohen, Duke, Head, Hogg, Hubbard, Jimack, Ranner, Ruddle, Pretorius, Xu)

Our approach is to embed fundamental developments in algorithms and cutting edge computational modelling within a framework that is guided by end-user pull (£300k direct financial support from NAG, Shell and Procter & Gamble). For industry partnerships and commercialisation, see REF3a. Other users and collaborators include the health sector and academics across maths, physics, chemistry, materials, engineering and the life sciences (see BMH). Achievements include:

- Fundamental **algorithmic developments for scientific computation**, from novel continuous/ discrete models ([Bollada1; Hubbard1,4; Jimack2,4; Ranner1], EP/G003645/1) to improved solution methods based on multilevel techniques and/or adaptivity ([Hubbard2; Jimack1,3], EP/F010354/1, EP/H048685/1) and massively parallel algorithms (EP/F010338/1, EP/I006737/1) have driven new understanding of aerodynamic shockwaves, complex fluids and solidification dynamics, from alloys to tumours.
- Integrating world leading contributions in computational topology [Carr1,4] and applications [Carr2] with work on systems [Duke1,4], we have established a top international presence in **scientific visualization**. Recent funding (EP/J013072/1, £920K) for cracking open the major long-standing problem of multi-field analysis [Duke3] already yielded novel insight in physics [Duke2].
- In visual analytics, Pretorius' collaborations (MIT's Broad Institute & Harvard) led to a novel tool for the optimisation of data processing pipelines [Pretorius1] and a Leverhulme Fellowship award, while Ruddle's work [1,2] is changing our fundamental understanding of how humans navigate.

Looking forward, we see extreme-scale computing and interdisciplinary collaboration as key pillars of our strategy: we will combine both stock and emerging technologies [Duke4]; algorithms that scale to high-complexity/volume data and high core counts [Carr1; Jimack3]; and new areas, e.g. human-in-the-loop decision-making [Pretorius1]. We will tackle challenges in engineering, physics and complexity science, building on our new EPSRC CDT in Fluid Dynamics (Jimack is PI), our world leading industrial partners (see REF3a) and cutting edge facilities (see Part d).

Applied Computing in Biology, Medicine and Health (BMH) (Atwell, Bulpitt, Cohen, Cohn, Head, Hubbard, Magee, Markert, Ruddle, Pretorius, Shakhlevich, Xu)

Since 2008, this activity has grown into a major SoC theme, incorporating significant contributions from every discipline of computing research within the school, supported by a substantial grant portfolio (~£3.3m primarily from EPSRC, BBSRC and the Wellcome Trust). Achievements include:

- Original computational approaches ([Cohen3,4] & EP/C011961/1, EP/C011953/1) pinned down the role of embodiment in the neural control of locomotion of a key biological system, spurring considerable new activity across biology, physics and robotics, and leading to Cohen's Leadership Fellowship (EP/J004057/1), Boyle's PhD Prize Fellowship and subsequent Lectureship. Our novel bioinformatics methods [Bulpitt1-3] have proved transformative for meaningfully combining data types; potential consequences now being explored range from land management [2] to disease [3].
- In biophysical modelling, fundamental contributions to computational algorithms directly led to insight on cancer growth [Hubbard3], with immediate interest from clinicians and collaborative follow-on funding (£1.2m EP/K039342/1, £265k to SoC). Predictive models of stochastic DNA transcription have elucidated molecular copying processes [Cohen1] and their error correction

mechanisms [2] while Head's original approach [1,2,4] led to several breakthroughs in modelling dynamics of biophysical structures, with potentially important biomedical implications.

- Collaboration with pathologists (Leeds Institute of Molecular Medicine and Leeds NHS Trust) have led to breakthroughs in 3D imaging ([Magee4], featured on the front cover of the American Journal of Pathology) and transformed large scale Powerwall technology from an expensive research instrument into a profoundly innovative tool for digital microscopy ([Ruddle3,4], Imaging Prize at Pathology Informatics 2011). For commercialisation of [Magee1,2,4; Ruddle4], see REF3a.

Looking forward, we will: (i) develop systems and tools for biomedical data analysis, from histopathology to NLP, e.g. building on clinical collaboration with Tuebingen [Markert2] to diagnose schizophrenia; (ii) deliver cutting edge computational models and algorithms, e.g. building on Head's collaborations (Leeds Dental Institute) to study pathogenic bacteria, with direct clinical/ industrial applications; (iii) grow collaboration across SoC, the NHS + Health & Social Care Information Centre, and with industry (JISC and new TSB NETIMIS grant with X-Lab, £347k), to build infrastructure and analytical tools for secure, large-scale patient data systems. To underpin this research, Hogg is co-I on a recent £5.7m MRC bid for a Leeds Medical Bioinformatics Centre.

c. People, including:

i. Staffing strategy and staff development

Staff recruitment and development has been guided by our strategy of investing in core strengths, while supporting intra and inter-theme collaboration as well as applied interdisciplinary research. **Staffing strategy:** Specific strategic aims achieved through academic recruitment include:

(i) **Strengthening foundations** in AC (responding to Dyer's reduced FTE load), in AI (following Everingham's tragic loss, a rising figure in computer vision on the international stage, and Hogg's Pro VC role) and in CSE (addressing Duke and Jimack's roles of Head of School and Faculty Dean). Appointments include Beyersdorff, Carr, Bollada and Ranner. E.g., Beyersdorff provides entry to computational logic (AI) and cryptography (AC). An additional CSE aim was increasing capability in 'big data' (Carr, Pretorius). Carr's leading international reputation in computational topology and extensive international collaborations rapidly led (with Duke) to key breakthroughs in the visualization of massive high-dimensional data ([Duke3; Carr2], EP/J013072/1). **We actively support frequent outward sabbaticals and inward visits** (typically having multiple visitors at any time) to promote collaborations. E.g. Michael (visiting Cohn) is one such short-term Lecturer.

(ii) **Broadening multidisciplinary activities while promoting computational thinking in other disciplines:** We strengthened links with Mathematics (Beyersdorff, Ranner), Process and Material Engineering (Bollada) and Medicine (Pretorius, Head). E.g., Beyersdorff's appointment has strengthened links with the Logic and Algebra group in Mathematics, already leading to a joint seminar series. Pretorius' expertise in virtual reality (with Ruddle) exploits Leeds specialist facilities (the Leeds Powerwall) to further our existing collaborations in histopathology. Head and Pretorius (tenure-track Senior Translational and Leverhulme Fellows) link CSE and BMH research. Head provides further translational links with oral dentistry and Pathogen Control Engineering (in Civil Engineering), and is working to establish Leeds as a leading international hub of biofilm research.

Specific areas of growth identified for **investment over the coming years** (pervasive computing, big data, robotics) are aligned with strategic plans, national & international priorities (Pt b, REF3a).

International staff appointments: Most recent academic recruits were from outside the UK (as were Head and Pretorius). Recruitment of these internationally leading researchers has had a multiplier effect on the School's capabilities, as each has brought to the School a network of outstanding international collaborations (e.g. Galesi, Hagen, Razborov, Pasucci and Valiant).

Academic promotions include two Chairs (Cohen 2010 and Vušković 2012); two Readers (Markert 2011 and Ruddle 2010) and two Assoc. Prof. (Atwell 2013 and Dimitrova 2012). Our probation scheme (two years for ECRs and RAs, longer for tenure-track Fellows) provides close mentorship, e.g. in grant applications, and priority in School DTA allocation.

Career development support: We ensure substantial quality time (at least 40% of the nominal workload) to research-active staff at all levels, with opportunities to pursue new or speculative research. Probationary staff have a reduced teaching and administrative load, as do staff with substantial grant portfolios. Additional support (RAs) offsets substantial administrative roles (Duke, Jimack, Hogg). RAs and RFs are offered teaching, PGR co-supervision (6 in current cohort), grant leadership (Beck - an FREng ERA Foundation Entrepreneurs Award finalist - championed the open

science DART project, including extensive dissemination activities. e.g. in Science festivals; Townend helped prepare and is the lead software architect on the TSB STRAPP project), and organised conferences (several in Leeds, China, San Francisco and more; 3 PC chairs); editorial positions held include Phil.Trans.R.Soc.A special issue on clouds.

Personal research fellowships won in an open competition: Encouragement and support for staff to apply for external fellowship schemes is integral to our strategy. An extensive support system mentors applicants through the application process (see Part e for Fellowships awarded).

Research leaders of the future are identified at all levels of seniority and provided with opportunities and mentoring for career advancement. RAs and ECRs are supported in their development and applications for fellowships (e.g. Pretorius' Leverhulme). At the more senior level, the University's flagship 'Tomorrow's Leaders' programme was attended by established/emerging leaders; from 2008: Bulpitt, Cohen, Dimitrova, Duke, Djemame, Hubbard, Ruddle, Vušković.

Over the REF period, eight members of staff have benefitted from an annual **sabbatical scheme**. Two sabbaticals were supported by Humboldt fellowships, and Vušković's extended (two year) leave was part-funded through secondment in Belgrade. 2.5% of research grant income is set aside for PIs to re-invest, e.g. to increase reach and impact of research, for small equipment, or to seed-corn new lines of inquiry. Further School funds support visits, conferences, and staff training.

We implement the Concordat to Support the Career Development of Researchers: In line with the University's Employment Policy for Research Staff, we support the career development of researchers through (i) an effective induction into the School and University, (ii) a structured probation programme with clear personal targets, (iii) an annual academic meeting, and (iv) access to staff development, funded by the School. Annual Academic Meetings identify academic and developmental needs, mechanisms for support and opportunities to adjust workload, for example increasing buy-out to provide time to lead a substantial research activity (Cohen, Cohn, Dimitrova, Xu). In addition, longer-term career plans and development are reviewed in individual, annual *Staff Review and Development* meetings. Outside of annual milestone meetings, regular reviews with mentors and the School's Director of Research allow staff to discuss research progress and plans.

Supporting equality and diversity: We have a thriving body of international staff and students including academics from across Europe, the Middle East, North Africa, and the Far East. Our ethos of equality and diversity is evident in our conduct, from recruitment (interview panellists are always E&D trained), through staff and student development, to promotion (four of six recent promotions were women). The Leeds Bronze Award under the Athena SWAN Charter for Women in Science was recently complemented by a Faculty Bronze award (2013), reflecting our commitment to the career progression of women. SoC support, and flexibility, to a number of our staff with young families (including both Chair promotions) has allowed them to maintain research momentum and excellence. Networking, support and mentorship are offered, e.g. in weekly meetings of our *Women in Science, Engineering and Technology* (WiSET) network, again with active SoC participation. A SoC RA (Dee) deputy Chaired BCSWomen (group for women in IT) and founded the national Lovelace Colloquium for women students of computing (2008). In 2011, PhD student Kerrison won the *London Hopper Colloquium Prize* and was the 2012 *invited speaker*.

ii. Research students

PGR Recruitment, approaches and discipline specific issues: With 58% international students, we attract a large number of self-funded and government-funded PGRs. Open PGR positions are advertised nationally and internationally. Extremely thorough selection includes interviews by two staff either in person or by video/phone with further vetting by the PGR admissions tutor.

We are extremely successful in recruiting students that are funded through highly competitive national and international scholarships such as Leeds University Research Scholarships (~1 award a year), Leeds International Research Scholarships (~1 award a year), Leeds Endowed Scholarships, Commonwealth Scholarships and a wide range of flagship scholarships from overseas governments including Pakistan, Saudi Arabia, Mexico, Thailand and Brazil. To facilitate these exchanges, the School and/or University offers reduced fees to the very best students from some countries (e.g. Mexico). Industry-funded scholarships include contributions and Case Studentships, from large (e.g. Microsoft, BAEs, JLR), medium-sized (e.g. Tracsis, see Impact Case Study) and small companies (e.g. media company Zoo). International sponsorship includes, e.g. a Commonwealth Scholarship to Danso to conduct fieldwork data collection in Ghana.

Training & support mechanisms: To enable shared experience, vibrancy and synergies, our PGRs are fully embedded in a research team, participating in weekly theme-based (and often additional project-based) seminars, academic activities and a vibrant PGR social life, theme-centred and School wide. PhD students are treated with equal status to research staff in all practical respects: PGRs work alongside PDRAs in generous purpose-built research accommodation, an arrangement valued by all for informal support that generates a strong research ethos. A monthly PGR forum provides a regular communication pipeline between the School, supervisors and PGRs. **PGR provision** includes a new workstation, dual-display monitors, access to all facilities, and funding for at least two international conferences. Further conferences, schools and research trips are funded by scholarships (e.g. NSF; NATO Advanced Study Institute), bursaries, or staff/project funds. Open competition is encouraged for PGRs to attend the best summer schools in core and interdisciplinary areas from AI to quantum information.

PGR student training is of the highest standard: Every PhD student has an experienced primary supervisor, and either a mentor or second supervisor (all formally trained in PGR supervision) with interdisciplinary supervisors as required (presently ~25%). Further input is received from non-supervisors at annual reviews. The postgraduate tutor and mentor provide further general, developmental and research support. **Progress monitoring:** Weekly supervision meetings with PGRs are the norm, with at least one formal, minuted, monthly meeting. A qualifying oral exam (year 1) includes a research-paper style report. Six-monthly reviews monitor progress and identify research, training and development needs. Our PGR programme provides subject and industry-relevant training, career development and a rewarding student experience:

- Every PGR participates in a tailored induction programme covering expectations, support structures and mechanisms, as well as fundamental research skills.
- Within one month, the student and supervisor agree on an individualised training plan. Each PGR maintains a Professional Development Plan with regular input from mentors and supervisors.
- PGRs attend workshops, courses and events organised in the School or provided by our Training and Development Hub for STEM subjects and the University's Development Unit. Specialist multidisciplinary training is tailored to student needs. Additional courses and activities develop employability awareness and skills, and provide interaction and contacts with industry.
- All PGRs attend (and most present in) the weekly School Colloquium and the seminar series in their research area and, to a broad audience, the Leeds Annual Postgraduate Conference.
- Vibrant professional and social activities (PGR Maths Club, outings to industry, most recently AQL Data Centre, Bletchley Park, hiking trips, etc.) are organised by PGRs, assisted by staff and supported by School funds and facilities. The annual SoC **PGR Symposium**, organised by and for PGRs, features research presentations by the students and inspirational careers-related talks. Best talk prizes are one of many examples of how we recognise and reward PGR achievements in SoC.
- Training for teaching and opportunities to lecture, to support undergraduate teaching & projects, and to participate in SoC summer camps and other outreach activities offer valuable experience.

The success of our PGRs is evidenced by high completion rates (~90% since 2008), prizes and awards (2012 Sullivan Thesis Prize awarded by the British Machine Vision Association; *Rob Fletcher prize for best student paper*, Eurographics UK 2009; *Best New Neuromorph of the Year*, Neuromorphic Engineering 2009; *London Hopper Colloquium Prize* 2011 *& invited speaker* 2012; and *best paper award*, ISORC 2012). Of our post-2008 graduating cohort, five are **permanent academics** at prominent UK universities (Bristol, Manchester, Aberystwyth, Leicester, Leeds); ~12 have returned to permanent academic positions in their (8) home countries. Recent graduates have won six (Brunel, MRC, NERC, ESRC, two EPSRC Doctoral Prize) **independent Fellowships** and many hold **R&D** positions (e.g. in Xerox Research Labs, Grenoble; Innovative Scheduling, FL; Microsoft, MA; VP R&D of 365 Media Inc; 2x Continental, Germany; 2x Irisys, UK).

d. Income, infrastructure and facilities

Investments (both current and planned) in infrastructure and facilities: Our spacious accommodations are centrally located in the main campus. All staff and PGRs work in a modern, well equipped environment with fully-supported high-performance and specialist computer hardware; a dual-display workstation configuration was rolled out across the School. Extensive research support includes a well-embedded technical support team (~10 staff) that ensures all our

PGRs and staff have equipment, software and infrastructure to suit their research needs.

A matched Capital Fund provides a 50% University contribution to resources over £25k, and a searchable database facilitates equipment sharing across the University. Major School-wide refurbishment in 2007 meant that facilities were up to date throughout the REF period. In 2012, a £125k (capital fund) was used to match School support for a substantial refurbishment including enhanced office spaces for research staff. To support growing collaborations, e.g. with the Centre for Regenerative Medicine, new Centre for Mechatronics & Robotics and new Centre for Integrated Energy Research, we plan to move our premises into the Engineering precinct; a ~£4.5m capital bid will fund renovation, extension and customization of an existing building, including new laboratory space/facilities for developing areas (mobile/pervasive computing and robotics).

Provision and operation of specialist infrastructure and facilities: SoC researchers have been instrumental in developing a range of specialist equipment. **DSS** created an in-house cloud service to develop and stress-test new services and middleware in a controlled environment and play a leading role in **hosting/operating the White Rose Grid (WRG) e-Science centre** (>£2m UK National Grid Service & EPSRC funding, including Platform grant) providing support to numerous scientific and industrial applications; regarded by EPSRC as an exemplar of success (1 of only 4 centres, from around 16 UK e-Science centres, to receive full10-yr funding), it led to Xu's appointment as Coordinator of EPSRC's International Review on e-Science (2009). Supporting this is an in-house cloud service that DSS use to develop and stress-test new services and middleware in a controlled environment. **BMH** work makes extensive use of large-scale displays (7x4, ~54M pixel, and smaller 4x3 Powerwalls). Growing **AI** activity in autonomous systems uses a €30k robot and the recently inaugurated EPSRC National Facility for Innovative Robotic Systems (£4.3M; Cohen and Cohn, co-Is). We played a leading role in establishing the Leeds Software Repository, promoting research software, providing a single user-ready University portal for open access downloads (see Part 3a). Dedicated IT appointments have supported this activity and all themes have already benefited. State-of-the-art computing facilities (7,552 cores) are free at point of scientific use (supported by £1m biennial UoL investment). UoL also hosts the N8 HPC facility (£3.25m from EPSRC, Co-Director Hogg) on behalf of N8 universities, providing >5000 cores.

Research funding portfolio and future plans: Building on our strong trajectory over 2001-07, we continued to boost research funding, from £8m in RAE 2008 to £12.1m in REF14, or £97k/fte per annum), and diversified our income sources. Strategic efforts to broaden our funding base and pursue larger collaborative grants led to a substantial £2.4m increase in EU funds. We achieved this through new support staff, structures and resources to PIs (time, travel funding, including travel for EU grant applications, reduced workload and internal peer review offered for all grant applications). Our strong alignment with EPSRC priorities in 3 of 4 "challenge" areas – sustainable society (transport, hospital scheduling); communities and culture (natural language corpora, knowledge management); IT as a utility (distributed services; energy-efficient data processing) – yielded a further £1.3m growth (from UKRCs). We also made significant investments in staff in our faculty Research Finance Office, who, together with the UoL's European Office provide support in all aspects of preparing and running research grants, in particular fellowships, large and EU grants.

e. Collaboration or contribution to the discipline or research base

The success of our strategy is evidenced, first and foremost, in the impressive **volume and quality of our publications**: ~675 international peer reviewed research publications by SoC authors over the REF period (with 45% journal articles) have generated considerable academic impact including ~5000 G-scholar citations (~3000 for 2008-09 papers). >50% of our REF2 outputs (2008-2011) are in the top 10% in Scopus citations (Computer Science) for their year.

We have joint projects with every Faculty in which 'computational thinking' forms an indispensable part of the discipline; this ethos extends to PGR training, with consistently high numbers of PGRs co-supervised with other disciplines (~25% of the current cohort). Our **outward thinking** and **engagement** has consistently given rise to new research capabilities with broad international impact: from *gcc* and *Haskell* compiler software [Duke4] & activity analysis [Cohn2,4; Hogg1,3,4], to physics [Duke2], medical imaging [Magee1-4], cancer [Hubbard3], histopathology [Ruddle3,4], psychiatry [Markert2] & social science [Lau2]. All these will deliver societal impact in coming years.

Industrial partnerships with leading national and international companies drive us to translate research to software solutions, e.g. in DSS alone: cloud service performance evaluation (with

Flexiant and **Atos**, France [Djemame2]), cloud computing brokerage (**BT** [Djemame4]), quality of Service in remote health monitoring for aerospace engines (**Rolls-Royce** [Djemame1]), and cloud data management (**Google,** USA [Xu3]). See REF3a for further examples.

Our efforts to recruit and develop staff with outstanding international records has borne dividends in underpinning >20 substantial international collaborations (10 USA, others across Europe, Australia, Brazil, Canada, China, Israel, Japan, Morocco, Pakistan). Our REF2 outputs include >80 international authors. In AC alone, **world leading collaborators** include Galesi (5 papers, 2 grants, joint workshop); Razborov (2 papers); Brucker (3 papers); Trotignon (grant, 9 papers) and MacArthur Fellow Chudnovsky (2 papers). Collaborations have also benefited SoC through extensive two-way exchanges (>45 visiting scholars, >30 from overseas, 1 week to 1 year stays).

Outstanding results from **partnerships with end-users** range across all themes (see REF3). E.g. our cutting edge CROWN-C middleware system (Computer 2008; [Xu1]) rapidly impacted cloud services (exploitation by Inspur, China-Mobile, Teamsun). CSE software [Jimack2-3] was provided to Shell, Lucite, Dow. Histopathology software has been [Magee2] or is being [Magee4, Ruddle4] commercialised. Our ontology creation tool (ROO, >1000 sourceforge downloads, Ordnance Survey collaboration) is used by experts in several domains ([Dimitrova2], NeTTUN with SNCF.

High profile activities and honours evidence our world leading contributions and leadership:

- **Invited Talks:** >30 keynote and plenary presentations by more than ten members of faculty and ~35 further invited talks in international meetings and conferences.
- **Conference Chairing/Organization:** Our staff have had leading roles in >50 international conferences, including 17 Conference Chairs/Co-Chairs, e.g. CVPR 2010 and EuroVis 2013.
- **Open competition Fellowships:** Cohen: EPSRC Leadership 2011-16; Markert: Alexander von Humboldt (Experienced Researchers – ER) 2011-13; Ruddle: Alexander von Humboldt (ER) 2008-09; Pretorius: Leverhulme Early Career 2013-18. Boyle, Washtell, Ranner: EPSRC PhD Prize.
- **Awards and prizes:** Cohn**:** Distinguished Service Award AAAI – the very first such distinction awarded outside N. America; Cohn's VAULT system won the 2012 IET Innovation Award (Built Environment), was highly commended for the IET award (IT) and won the 2012 NJUG Award (Avoiding Damage); Xu: IEEE Service Award for RTSOAA 2011; Dyer: Eur. Assoc. for Theoretical Comp. Sci. Award 2013; Hogg IPRA Fellow 2012 & BMVA Distinguished Fellow 2011; Head: APS outstanding referee 2009; 8; Ruddle BCS Fellow 2013; **8 Best paper awards** and [Beyersdorff3] selected by ACM Computing Reviews as among the 11 best Theory of Computing papers and among the 91 best papers across all of CS published worldwide in 2012; PGR prizes: see Part c.
- **Advisory and Steering boards:** ~10 of our academics, including: Cohn: Director of KR Inc, Advisory Board (AB) of Int. Assoc. of Ontology & its Applications; UKCRC Exec. Comm.; REF2014 panel member; Dimitrova: Exec. Comm. of Int. AI in Education Society; Duke: Exec. comm., European Assoc. for Computer Graphics; Jimack: Exec. Comm., Global Engineering Deans Council 2012-2015; AB, NAG Ltd; Xu: Exec. Board – IEEE Technical Comm. on Business Informatics Systems; >5 international Steering Committees, including the IEEE Conf. on Cloud Engineering (Founder); Chair, International Academic AB for ICT, Chongqing U.; Academic Comm., Chinese National Key Lab on HPC. Additional **contributions to the research base** include Hogg's service on EPSRC's ICT Strategic Advisory Team and Carr & Kirkham's participation in the Royal Society Pairing Scheme. **Consultancy work** by SoC members varies from service to industry (e.g. Shell and Apollo Medical Information Systems) to basic research (e.g. survey analysis for EarthWatch and ontological research for SRI International).
- **Editorial boards:** We serve as board members for ~30 international journals, including AIJ (Editor in Chief, EiC) and SCC (EiC); AAAI Press (EiC); J. Applied Logic; IEEE TLT J., J. of Discrete Algorithms, SIAM J. on Optimization; SIAM J. Scientific Comp. (Assoc. Ed.); Applied Numerical Math. (Senior Ed.); J. of Public Transport (Senior Ed.); Planning and Operations; Comp. Linguistics; IEEE PAMI (Assoc. Ed.); guest ed. positions include, e.g. special CVPR issue 2010.
- **Major challenges and competitions led by our staff** reflect our international leadership and contributions to a variety of computing disciplines. E.g. our competitions for Metonymy Resolution [Markert1] and Visual Object Classes (PASCAL, Everingham) have provided key resources that opened new avenues of research; both proved to be agenda setting in their discipline.
- Frequent media reports on our research (e.g. 30 min. on Radio4, Digital Planet, New Scientist, Wired) & extensive **public engagement** (eg. science festivals, shows, Headstart Summer School).