Institution: University of Cambridge

Unit of Assessment: B11 Computer Science & Informatics

a. Overview

This UoA coincides with the University of Cambridge Computer Laboratory ("the Laboratory"), which is the University's academic department of computer science and is part of the University's School of Technology. The Laboratory is housed in the William Gates Building. This 10,000 m^2 building was purpose-built for the Computer Laboratory. It opened in 2001, with the Laboratory occupying two-thirds of the space. The Laboratory now occupies almost the whole building.

At 31 October 2013, the Laboratory has 41 academic staff, 5 research fellows, 81 contract researchers, 2 affiliated lecturers, 119 PhD students, and 46 Masters students. There are 29 support staff (administrators, computer officers, and technicians).

The Laboratory has eight research groups, which are loose affiliations of like-minded researchers. Several academic staff belong to more than one research group. The groups are Artificial Intelligence; Computer Architecture; Digital Technology; Graphics & Interaction; Natural Language & Information Processing (NLIP); Programming, Logic & Semantics; Security; and Systems.

b. Research strategy

The Laboratory has an exceptionally broad range of research interests at internationally leading standard, from pure theoretical computer science to micro-processor architectures, from wireless communication hardware to the psychology of programming. The Laboratory consistently ranks in the top 10 computer science departments worldwide (QS World Rankings). The world-leading expertise of its academic staff leads naturally to the Laboratory's research strategy, which is to allow each academic, or group of academics, to drive their own research. The quality of the academic staff and their passion for their own research make it inappropriate and inadvisable to impose a top-down research strategy. The management team in the Laboratory therefore concentrate on providing an environment and a support structure in which the Laboratory's research can flourish, providing a light-weight steer on appropriate ways to enhance that research, and providing a long-term strategic view on recruitment and research funding.

While each academic member of staff is free to pursue their own research interests, the principal focuses of research are reflected in the eight research groups. The groups bring together the expertise of between three and twelve academic staff. The boundaries of the groups are both mutable and permeable, with many staff members belonging to more than one group. The research can be further amalgamated into three broad areas in which the Laboratory has a large number of outstanding researchers: systems research (encompassing the Systems, Computer Architecture, Digital Technology and Security research groups), machine intelligence (the Natural Language & Information Processing and Artificial Intelligence groups, along with parts of the Graphics & Interaction Group), and theoretical computer science (the Programming, Logic and Semantics Group). The three most recent academic hires have been to consolidate each of these three areas: Watson (2013) has expertise across all four of the research groups that are broadly "systems", Sauerwald (2013) consolidates links between programming and logic in the theory area, and Clark (2009) brought strong new expertise to the NLIP group, particularly in the area of machine learning applied to natural language problems.

While the groups provide focus, an important characteristic of the Laboratory is a collaborative culture without intellectual or group balkanisation: interactions occur in all patterns across theory, practice, technology and engineering. Since 2006 there have been annual, well-attended off-site meetings of all academic staff which include discussion of new research themes.

The Computer Laboratory plays a part in four of the University's wider Strategic Research Initiatives. In the *Energy@Cambridge* initiative, the Laboratory collaborates in the cross-cutting theme Smart Systems and Device Design. The highest profile contribution here is Hopper's Computing for the Future of the Planet. In the *Cambridge Neuroscience* initiative, Robinson has worked with psychologists investigating the boundaries between people and computers, most notably in automatically assessing human mental state from facial expression. In April 2009, he organised a two-day Royal Society discussion meeting on Computation of Emotions in Man and Machines. Copestake is a member of the steering committee for the *Cambridge Language Sciences* initiative. Crowcroft is a member of the steering committee for the *Big Data* initiative. The

Laboratory participates in three of the University's Strategic Research Networks in *Digital Humanities*, *Nanotechnology* (NanoForum), and *Sensors* (Cam*Bridge*Sens).

In 2009, the Laboratory introduced a new MPhil in Advanced Computer Science as a one-year bridge between undergraduate and PhD degrees. This was partly in response to staff members' increasing concerns that students with only an honours degree were ill-prepared for PhD research and partly as a recruiting ground for PhD students. While recognising that other universities offer excellent Masters courses, it was accepted that Cambridge lacked this element in its portfolio of research training. The academic staff embraced the opportunity to teach, work with and assess students before they commence a PhD. The MPhil has proven a good recruiting ground for the PhD, with about a quarter of the MPhil class going on to a PhD at Cambridge. Many others go to PhDs elsewhere or to industry. An integrated-masters MEng course was introduced in 2011, sharing many modules with the MPhil. The MEng allows local students to take a Masters course, funded on their existing student loan, as the UK otherwise has no structured funding for UK students to take the MPhil course. In 2013, half of the Laboratory's PhD intake had previously taken one of the Laboratory's Masters degrees.

Evaluation relative to RAE 2008

The Computer Laboratory has expanded in size since the RAE2008 submission was written, with five permanent academic appointments having been made. Four of those were new lectureships. The fifth (Mascolo) was to fill the vacancy left by Fraser's resignation to work full-time on the Laboratory spin-out, Xensource. Fraser is the only member of permanent academic staff to leave the Laboratory in the period 01/01/2008 to 31/10/2013. Since RAE2008, the number of contract researchers has increased by 138% (from 34 to 81). Three research groups (Graphics & Interaction, Computer Architecture, and Digital Technology) have moved into the top floor of the three-storey William Gates Building, which was previously occupied by commercial lettings. The Laboratory now occupies almost the entire building, with the single remaining tenant (a small outpost of the Department of Engineering) having informal notice to quit, as the Laboratory expects to need their space within the next five years.

Since 2008, the Laboratory's research work in automated reasoning, programming languages, theory and semantics has been drawn closer together by merging these into a single research group: Programming, Logic and Semantics.

With regard to the strategic aims presented in the RAE2008 submission:

General expansion: The aim was to recruit staff to five new academic posts. The new environment of austerity made this challenging. However, the University supported the Laboratory's case that this UoA should expand when others were being asked to contract. The Laboratory was thus able to create four new permanent posts in the period. This expansion is largely due to the considerable income that the Laboratory brings to the University through its research. The Laboratory has more than doubled its annual research income (£6.3M in 2012–13 cf. £2.8M in 2006–07), hence the concurrent expansion of its contract research work force by 138%. This is an excellent outcome under a regime of financial austerity.

Computer Science for the Future of the Planet: Hopper has spoken on the topic dozens of times since his seminal paper in Philosophical Transactions of the Royal Society. Hopper's approach to the topic has become accepted wisdom across the community. The Royal Society organised a conference on the subject in 2013. Computing for the Future of the Planet is both a research topic in the Laboratory and a project in the University's Energy@Cambridge strategic research initiative. Computing for the Future of the Planet was one of 13 recipients in the first ever round of Google Focussed Research Awards, receiving a $400,000 unrestricted award in 2010.

Expand Digital Architecture research: The Computer Architecture group, led by S Moore and Mullins, is thriving. The group recruited Jones (RAEng Research Fellow), who provides an excellent third PI to the group. It collaborates heavily with researchers in the Digital Technology Group. The Laboratory's research work with DARPA has pulled together the three research groups in Security, Systems, and Computer Architectures. The new appointment (Watson) will further consolidate this cooperation across the discipline.

Recruit fourth permanent academic in NLIP: Clark was recruited in 2009.

Develop interdisciplinary work on psychology and security: Anderson has led this drive over the past decade. He was one of the founders of the international, interdisciplinary, invitation-only Workshop on Security and Human Behaviour, held annually since 2008.

Endow the Chair of Computer Technology: Negotiations with a commercial sponsor are in train.

Strategic plan

The Laboratory aims to continue to excel in world-leading research and wealth creation across a broad spectrum of computer science. Subject to finance, the Laboratory plans to expand the academic staff by four more people over the next five years. Strategically, those expansions will be into areas that strengthen the Laboratory's research portfolio in two ways: consolidating existing expertise (e.g., Clark's appointment to the already excellent NLIP group) and bridging the gaps between existing disciplines (e.g., Watson's appointment to bridge between Systems, Security and Architecture). Support functions (e.g., grant administration) will also be expanded. Beyond 2020, there will need to be new building to house any further expansion in staff. Progress against these plans is monitored by the Senior Management Team, comprising the Head, two Deputy Heads, and Departmental Secretary, advised by senior administrators and academics. The Team dynamically assess the effectiveness of policies, hiring strategies and grant applications. The Laboratory's strategy, and tactics for achieving it, is discussed formally at the annual, well-attended off-site meetings of all academic staff, held in July. Aspects of strategy and management are also discussed, and views taken, at the weekly staff meeting and by e-mail circulation.

c. People, including:

i. Staffing strategy and staff development

The Laboratory's recruitment model is to identify areas in which the Laboratory's research portfolio needs to be strengthened, and to recruit into that area the best person available. In assessing need, the Laboratory considers both internal strengths and weaknesses and also the international research landscape. Over the period, five permanent academic staff were recruited into the areas identified as being of most need. For instance, the appointments in systems (2008), natural language (2009) and digital technology (2010) were as a result of identifying groups that needed more research resource. In addition, those appointments committees chose candidates who enabled a strategic focus on mobile communications and social networking from three different perspectives. The two 2013 appointments were into areas identified as bridging existing strengths. One (Watson) was to work across the broad areas of systems, security and architecture; the other (Sauerwold) to work in algorithms, bridging between the existing work on complexity and on programming. The five new permanent staff are:

Mascolo	appointed 2008,	PhD 2001 Bologna,	previously Reader at UCL
Clark	appointed 2009,	PhD 2001 Sussex,	previously Lecturer at Oxford
Rice	appointed 2010,	PhD 2007 Cambridge,	previously post-doc at Cambridge
Watson	appointed 2013,	PhD 2010 Cambridge,	previously post-doc at Cambridge prior to his PhD he worked for six years in a series of US industrial research labs, including SPARTA ISSO and McAfee Research
Sauerwald	appointed 2013,	PhD 2008 Paderborn,	previously at Berkeley, Simon Fraser, and Max-Planck-Institut für Informatik (MPII)

The Laboratory has a relatively flat age profile for its permanent academic staff, with roughly even numbers of staff across all age ranges. Only three members of staff are over the age of 60, so only three retirements are expected in the remainder of the 2010s. There will be a cluster of eight retirements in the early 2020s. The Laboratory's strategic plan is to smooth out the 2020s cluster by using strategic reserves to recruit early to some of the posts. The Laboratory will assess research and teaching needs afresh for each post and not naïvely re-appoint to the same area.

Promotion to personal Readerships and Professorships is available to all permanent academic staff. It is run through an annual highly-structured competitive exercise with final decisions made by a committee chaired by the Vice-Chancellor. Promotion requires evidence to demonstrate a significant international research reputation, supported by objective criteria and strong external support. There is also a post of Senior Lecturer, for which a candidate must be able to demonstrate excellence in research, teaching, and overall contribution to the University. Over the REF period, the following have been promoted:
to Professor: Daugman (2009), Dawar (2009), Dodgson (2010), Copestake (2011), Fiore (2011),

Sewell (2012);
to Reader: S Moore (2008), Sewell (2008), Hand (2009), Mascolo (2009), Teufel (2010), Gibbens (2011), Clark (2012), Griffin (2012), Liò (2013), Stajano (2013);
to Senior Lecturer: Griffin (2008), A Moore (2010), Kuhn (2010), Jamnik (2011), Beresford (2013), Harle (2013), Mullins (2013), Rice (2013).

The Laboratory is particularly successful in its promotions. It is notable that there is currently no backlog of promotions applications in the Laboratory: all applicants were successful on their most recent application, with 88% of applicants being successful on their first application in the REF period. This compares against a University average of 56% of applicants being successful on any application in the REF period. It demonstrates that the Laboratory is supportive of its staff and that the staff are of high academic quality.

Permanent academic staff are entitled to one term of sabbatical leave on full pay for each six terms of service so that one year can be accumulated by six years of continuous service. Most staff make full use of this entitlement to refresh their research outlook and expertise, often at other universities overseas and for which the University or Laboratory frequently assists towards travel costs. In the reporting period, 22 academic staff took sabbatical leave out of a possible 30 (this number omits staff who had taken leave just before the period and staff who were appointed during the period).

The Laboratory has a wide range of academic visitors. Previous visitors include Prof. Bjarne Stroustrup (2012–13, on sabbatical from Texas A&M), Prof. Fred Brooks (2008, visiting for several months from UNC Chapel Hill). Amongst current visitors (July 2013) are Prof. Sir Tony Hoare, Prof. Keith van Rijsbergen, Pilgrim Beart (entrepreneur), Prof William Webb, Prof. Rafael Calvo (on sabbatical leave from U. Sydney), Prof. Warren Hunt and Dr Kaufmann (both from UT Austin), Dr Slobodova (Centaur Technology) and Dr Malcolm Sabin (winner of the IMA's gold medal 2012).

The University has considerably more generous maternity/paternity/adoption leave provision than required by law. It also offers a graduated return to work plan, flexible working arrangements and recommends that major Departmental meetings should be held during core working hours so that parents of young children are not excluded. The Laboratory's weekly staff meeting, all other administrative meetings, and all research seminars are held within the hours 9am–5pm. The Laboratory's culture is that academic staff organise their own time, which gives parents and other carers the freedom to organise their work around their caring responsibilities. The University has recently introduced a new Returning Carers Scheme to help staff members resume their research on their return to work following a career break arising from caring responsibilities. This is open to men and women and offers various measures to meet particular circumstances, e.g., buying out teaching and/or administrative duties, funding attendance at conferences or providing the support of a researcher. Within the Laboratory, the best example of the use of the University's generous provision is a member of academic staff who took extended maternity leave (12 months) and returned to working half-time, with appropriately reduced teaching and administrative loads. Several other staff members have taken paternity leave during the period, two staff members were offered reduced work-loads while caring for terminally-ill spouses, and a number of staff members were supported through periods of significant ill health.

In common with many Computer Science departments, the Laboratory has a highly-skewed gender profile. Of the 41 academic staff, only 12% are female. The same proportion is true of under-graduates. Graduate students are around 20% female. In response to the even-lower proportions of female involvement a decade ago, in 2004 the Laboratory started the national women@CL network to address the gender imbalance in computer science, under the leadership of Jamnik and of Ursula Martin (who held appointments with the Laboratory and Microsoft Research Cambridge before her move to QMUL). The network provides local, national and international activities to inform and support women who are engaged in, or aspire to, careers in computing research and academic leadership. It was originally funded by an EPSRC Network Grant and now attracts funding from a variety of sponsors which have included IBM, Microsoft and Google. At the local level, women@CL uses a simple grass-roots model that is effective, replicable and sustainable across science and engineering departments in a complex institution. The most effective parts of the local provision are the monthly women@CL seminars (open to all, male and female), the regular women@CL dinners (women only), and the big-sister–little-sister mentoring scheme.

At a central level, the University noted a recent decline in applications from women for promotion to

senior academic positions. The University's HR Division and its Equality and Diversity Office are taking measures to reverse this trend and to ensure that the university develops a healthy pipeline of talented, qualified women to fill senior posts in the future. For example, development workshops have been introduced, as have mentoring schemes designed especially for female researchers. Although keenly aware that only five of the 41 academic staff are women, the Laboratory has a good record in the promotion of women, with two female professors (Bacon, Copestake), one being Deputy Head of Department; two female readers (Mascolo, Teufel); and one female senior lecturer (Jamnik). The percentages at each promotion level for women compare well against those for men (percentages of Professor:Reader:SL:Lect are 40:40:20:0 for women, 46:23:26:6 for men).

More widely, the University has set up WISETI, a scheme designed to support female academics in STEMM subjects. This has proved so successful that the University is considering extending access to all disciplines. The University is fully engaged in the Athena SWAN programme and has submitted its bronze renewal application. The Laboratory is preparing its own application for the SWAN programme. Between 2011 and 2013 the University won a number of awards for its work in engaging and working with staff, being ranked 11th (the highest for any UK HEI) on the Stonewall list (in 2012 and 2013) and winning an Employee Engagement award from the Employers Network for Equality and Inclusion (2012).

All academic and research staff have access to the training courses offered by the University's personal and professional development section. This includes training courses for academics, for leaders, and for staff early in their research career.

Early Career Researchers

In addition to creating new academic posts, and in response to an austerity agenda that threatened a moratorium on new academic posts, the Laboratory made a tactical decision to make more use of the post of Senior Research Associate (SRA); that is, to appoint independent researchers on research grant money, who direct their own research. These are early career researchers who have a good track record and are perceived to be on a rising trajectory. Almost all have already produced the required number of outstanding research outputs for submission to REF, given the length of their independent research careers, and all have been associated with world-class research, so that there is every confidence that they will develop into top quality academics.

The Laboratory also seeks excellent research fellows, who have been successful in external competitions for independent research funding. In the REF period the Laboratory has had eleven fellows funded by the Royal Academy of Engineering, the Royal Society, the EPSRC, and the EU. Currently in the Laboratory are Jones (RAEng, Computer Architecture), Korhonen (RS, NLIP, shortly to take up a Lectureship at the Cambridge Department of Theoretical and Applied Linguistics), Murdoch (RS, Security), Myreen (RS, Automated Reasoning), Yoneki (EPSRC, Systems). Those who left the Laboratory during the REF period are Sarkar (EPSRC) and Kristensson (EU, named one of 35 top young innovators of 2013 by MIT Technology Review), now both Lecturers at St Andrews; Gotsman (EPSRC), now Assistant Research Professor at the IMDEA Software Institute, Madrid; Coyle (EU), now Lecturer at Bristol; Bulling (EU), now Independent Research Group Leader at the Max-Planck-Institut für Informatik, Saarbrücken; and Abbes (EPSRC), now MCF (Maître de Conferences, roughly equivalent to Senior Lecturer) at Université Paris Diderot (Paris 7).

In addition to the SRAs and Fellows, there are over 50 other post-doctoral researchers. The Laboratory's ability to attract these high-flying fixed-term researchers adds considerably to its research capability and output. The high quality of the environment in which they are placed gives them access to world-class researchers and to the opportunity to conduct world-class research of their own. The Laboratory has a good track record of training its post-doctoral researchers to be excellent independent researchers with successful careers subsequent to their time at Cambridge.

The University adheres to the Concordat to Support the Career Development of Researchers, and the Heads of Department at the Laboratory and across the School of Technology are committed to providing support for Early Career Researchers. These researchers have a wide variety of backgrounds, prior experiences and future goals. Therefore, a variety of training opportunities are provided working within the standards of the Employment and Career Management Scheme for Researchers. These range from short classes considering career issues to the more intensive

Emerging Research Leaders Development Programme. Access to a Career Management Tool and specialised advice from the Careers Service are also available.

In the Laboratory there are biennial appraisals of all staff, where there is an opportunity to discuss career directions and tactics for the next two years. The Laboratory's appraisal process is designed to be both a light touch and useful in career development. It is explicitly disconnected from any considerations of salary level, which are dealt with through other routes. The Laboratory has a 100% success rate in participation in appraisal for the entire REF period.

In addition to this system of regular appraisals for all staff, early career researchers are each assigned a senior colleague as a mentor. There is an expectation that staff will eventually generate their own research funding and there is a natural progression from co-investigator to principal investigator on grant applications, fostered by the organisation into research groups. Senior members of research groups read and comment on papers and grant proposals before they are submitted. Group members may (second) review papers for faculty on conference programme committees; this is acknowledged, and has led to invitations to serve on programme committees or carry out refereeing work for journals.

ii. Research students

The Laboratory has a large, active and high-quality body of PhD students. PhD students are each supported by a sizable group of people. Each student is assigned both a primary supervisor and a second advisor. There is occasionally also a second *supervisor*, who may be external to the Laboratory or the University, facilitating interdisciplinary research. The second advisor is able to help when the supervisor is absent or if the student has problems with the supervisor. The graduate student advisor (an academic member of staff) and graduate student administrator (a member of support staff) are available to discuss problems. The head of graduate education (a deputy head of department) handles difficult cases and manages the Laboratory's travel and hardship grants. PhD students are also supported by the wider University (counselling service, graduate registry) and by their College (financial aid, housing, welfare).

Researcher development is fully integrated into the first year programme by way of a compulsory research skills module. It concentrates on the underlying skills required for research: critiquing academic papers, reviewing papers, writing papers, presenting research, designing experiments, and analysing experimental results. After the first year, PhD students are offered a programme of further training including foreign language courses, presentation and voice projection classes and a range of teaching and research-related courses offered by the University's personal and professional development section. The Microsoft Research Summer School, run annually, provides students with guidance on industrial research and engaging with industry. Researcher development activity is evaluated and refined in consultation with students by way of the Graduate Students Forum (a committee formed of student representatives chaired by the Researcher Development Coordinator). Each PhD student must submit a first year report, comprising a detailed PhD proposal, and must be interviewed at the end of their first year before they can be registered for the PhD degree. They must also submit a report and dissertation schedule at the end of their second year, and an update on this at the end of the third year. These processes are designed to support the student through the PhD, the aim being to ensure timely completion.

The research groups run a variety of weekly seminars and reading groups to which PhD students are expected to contribute. There is always an opportunity for a workshop or conference paper to be given to a group in advance for practice, timing and feedback. PhD students are encouraged to submit papers to, and attend, international workshops early in their research in order to make international contacts. The Laboratory has internal funding to support student travel to present at conferences (it supports about 25 students a year in this way), which is additional to travel funding available from research grants, scholarship bodies and the Cambridge Colleges. There is an extensive network of laboratories with which the Laboratory exchanges PhD students as interns; recent examples include HP, IBM (TJ Watson and Zurich), Intel Research (Berkeley), Sun, Google (USA and Europe), Microsoft Research, Bell Labs, and Max Planck Institutes. The Laboratory also participates in the UCL-Cambridge Centre for Doctoral Training in Photonic Systems Development, which collaborates with a range of leading companies and research centres worldwide.

The Laboratory takes around 25 PhD students each year. This is significantly more students than

can be supported by the EPSRC Doctoral Training Grant. In addition to DTG studentships, there are students with awards from the Gates Cambridge Scholarships, the Cambridge Commonwealth Trust, the Cambridge Overseas Trust, overseas governments funding their best scholars to study at Cambridge, and industrial sponsors. In the latter category, there are studentships funded by Qualcomm and Thales, and further studentships awarded from the pooled donations made by members of the Laboratory's Industrial Supporters' Club. In 2013, the Laboratory set up a University-funded studentship scheme for UK students on the MPhil, in recognition that, unlike overseas students, UK students have almost no sources of funding for Masters programmes.

All research students have access to the online resources necessary for research, including the ACM and IEEE digital libraries. There are extensive computing facilities supported by a team of five computer officers, a dedicated computer science library, and a range of facilities in the William Gates Building (a café, common rooms, kitchens, and recreation room with pool table and table-football). The research students organise a weekly social event "Happy Hour" every Friday at 5pm. Most research groups have either daily coffee breaks or weekly lunches to which the whole group is invited.

d. Income, infrastructure and facilities

The Laboratory's strategy for research funding is to combine a continuous stream of public funding, from EU, RCUK, and US Government, with industrial sponsorship. Public funding is achieved through responsive-mode applications to EU and RCUK, through responses to particular collaborative calls, especially with US Government agencies, and through personal fellowships. For example, four permanent academic staff currently hold ERC Research Grants (Winskel, Clark, Stajano, Mullins) and one holds an EPSRC Leadership Fellowship (Sewell). EPSRC Advanced Research Fellowships were held by Jamnik (2002–12) and Mascolo (2005–10). Complementing public funding, the Laboratory maintains links with local hi-tech companies and pursues links with larger industrial funders. For example, it holds research grants from Huawei, Microsoft Research, Jane Street Holdings, Boeing and Thales; and has also received substantial donations. Over the REF period, direct donations into the Laboratory have amounted to £2.3M, with the largest being from Google (£842k), Actel (£300k), Radiolinija (£240k) and an anonymous donation of £601k. The Laboratory has recently appointed a "research facilitator" (for three years in the first instance, 2013–16) to enhance further its engagement with industry.

Research funding has risen over the past six years, from £2.8M (2006–07) to £6.3M (2012–13). In 2010, the Laboratory made a strategic decision to diversify its portfolio of research funders to reduce exposure to the expected reductions in RCUK funding. In July 2011, the Laboratory's grant portfolio was 75% funded by RCUK, counting the total value of all active research grants. Twenty months later (March 2013), the portfolio of research funding had increased by 12%, but reliance on RCUK had reduced to 54%. This was owing to a doubling in research income from both the EU and US governments, a tripling in income from charity, and a quadrupling in income from industry.

The six highest value grants currently running are: REMS: Rigorous Engineering of Mainstream Systems (Sewell, EPSRC, £5.6M), Crash-Worthy Trustworthy Systems (Watson, DARPA, £2M), ECSYM: Events, Causality and Symmetry – The Next-Generation Semantics (Winskel, ERC, £2M), Mission Oriented Resiliant Cloud (S Moore and Watson, DARPA, £2M), OCaml Labs (Madhavapeddy, Jane Street Holdings, £1.4M), M3: Managing Many Cores for the Masses (Jones, EPSRC, £1.3M).

The physical infrastructure and facilities for research are in the William Gates Building, which was completed in 2001. The purpose-built building was funded by the Bill & Melinda Gates Foundation (£12.9M) and by the University (£7.5M). The building provides for a coherent physical organisation of office and laboratory space. Over the twelve years since moving in (2001–13), the Laboratory has expanded from occupying two-thirds of the building to almost fully occupying it. This expansion was fuelled by the expansion of the academic staff by 50% over that period.

The considerable in-house computing and communication systems are enhanced by the extensive network infrastructure provided by the University Computing Service; for example, the Laboratory's research has made extensive use of the University's dark fibre network around the city centre. The Laboratory is a core member of the PlanetLab system, the worldwide network of over 600 systems available to distributed systems researchers for the last 5 years. Crowcroft is a member of the

PlanetLab steering committee. The next phase of PlanetLab (and GENI) will make use of the Xen virtualization technology created by the Laboratory's Systems research group. The Security Group's TAMPER lab facility includes a variety of microprobe and electromagnetic spectrum-related analysis tools. The University has recently invested several hundred thousand pounds in the Laboratory's infrastructure, upgrading its central file server to the latest version of NetApp and upgrading the backbone network to 10Gbps fibre.

More widely, the Laboratory benefits enormously from the world-class facilities elsewhere in the University. The University's copyright library and extensive physical holdings of older journals are a considerable resource for certain areas of research. Several Laboratory researchers collaborate with the Department of Engineering in photonics and display technology; Engineering's fabrication facilities are vital to that research. About two-thirds of academic staff (and all students) belong to a Cambridge College, which provides extra facilities, including subsidised (or free) catering, accommodation for visiting academics, and additional funding to support travel and other research costs. The Laboratory is well placed on the rapidly expanding West Cambridge site. There are excellent cycle routes between the West Cambridge site and the University's other sites and a subsidised bus route between the three main sites (West Cambridge, City Centre, and Hospital).

In 2012, postdoctoral research workers became the largest staff group in the University (now over 3500 of a total of 9500). In response to this growth the University has embarked on a major property development in North West Cambridge. In the first £300M phase, due to open in 2015–16, high-quality and sustainable housing will be provided for over 600 postdocs and their families, as well as homes for graduate students and private sector housing, retail and social facilities. This development is immediately north of the Laboratory's building, which will make the Laboratory well-placed with respect to the new hub.

e. Collaboration or contribution to the discipline or research base

The Laboratory is, by nature, inter-disciplinary, covering an unusually broad intellectual space. It comprises staff with training and expertise in a wide range of disciplines and who conduct research that might elsewhere be considered engineering, mathematics, linguistics, psychology, philosophy, or biology, alongside research that is core computer science. Examples of fruitful interdisciplinary collaborations are Liò's work with biochemists and mathematicians (bioinformatics), Gibbens' work with statisticians (analysing road and network traffic), Robinson's work with psychologists (novel human interfaces), Stajano's work with magicians and scam artists (psychology of fraud) and Mascolo's work with zoologists (wildlife tracking). Interdisciplinary work within the University of Cambridge involves the MRC Cognition and Brain Sciences Unit (Korhonen), the Centre for History and Economics (Watson), the Centre for Science and Policy (Murdoch), the Centre for Research in the Arts, Social Sciences and Humanities (Blackwell), the Statistical Laboratory (Gibbens) and the Departments of Chemistry (Beresford, Copestake, Teufel, Wassell), Engineering (many staff), Experimental Psychology (Korhonen, Mascolo, Robinson), Physics (Briscoe), Geography (Wassell), Biochemistry (Holden), Veterinary Medicine (Yoneki), and Theoretical & Applied Linguistics (Briscoe, Korhonen).

Academic staff collaborate in research with a range of other organisations including the following.

Non-UK academic institutions: Barcelona (Mascolo), Berkeley (Anderson), CMU (Anderson, Paulson), CNRS Paris (Mascolo), Columbia (Teufel), EPFL (Yoneki), Ghent (Jones), Georgia Tech (Crowcroft), Harvard (Anderson, Jones), IIllinois (Copestake), Indiana (Anderson), John Hopkins (Clark, Copestake), MIT (Robinson, Watson), MPII (Dodgson, Sauerwald), NRIA (Gordon, Sewell), Oslo (Copestake), Potsdam (Copestake), Purdue (Sewell), Saarland, Germany (Jamnik) Sao Paulo, Brazil (Copestake), Siena (Jones), SMU Texas (Anderson), Stanford (Copestake, A Moore), TU Darmstadt (Dawar), TU Munich (Paulson), UMass (Gibbens), Wisconsin (Watson).

UK academic institutions: Birmingham (Jamnik, Mascolo, Staton), Brighton (Jamnik), Durham (Gibbens), Edinburgh (Clark, Jones, Paulson), Essex (Bacon), Heriot-Watt (Gibbens), Imperial (Bacon, Beresford, Wassell), King's London (Pitts), Leeds (Beresford), Manchester (Jones, Paulson), Newcastle (Anderson, Beresford, Blackwell, Wassell), Nottingham (Blackwell, Staton), NPL (Wassell), Oxford (Bacon, Clark, Mascolo), Queen Mary (Mascolo), Reading (Mascolo), Royal Society of Chemistry (Copestake, Teufel), Southampton (Beresford, Mascolo), Sussex (Clark), UCL (Anderson, Crowcroft, Mascolo), York (Clark).

Companies: ABB (Anderson), Bell Labs (Mascolo), BT (Trossen, Wassell), Celgene (Holden), Centaur Technology (Myreen), Google (Anderson, Hand, Mascolo, Watson), HP Labs (Yoneki), Huawei (Dodgson), IBM (Copestake, Gibbens, Mascolo, Sewell), Intel (Jones), Irisys (Bacon), Jane Street Capital (Madhavapeddy), Linguamatics (Copestake), Microsoft Research (many staff), Raytheon BBN (Gibbens), Samsung (Anderson, Mascolo), SRI International (Hand, S Moore, Watson), Stagecoach (Bacon), Thales (Bacon, Robinson).

Non-Governmental Organisations: FreeBSD Foundation (Watson), The Tor Project (Murdoch, who, for his work on Tor, received an EFF Pioneer Award and an Access Innovation Award in 2012, and was shortlisted for the Index on Censorship Freedom of Expression Award in 2011).

Academic staff have been visiting researchers at, for example, ARM (Jones, 2011–13), CMU (Anderson, 2011; Stajano, 2010), Google (Anderson, 2011; Beresford, 2011; Stajano, 2010), Harvard (Jones, 2010), IIT Bombay (Mycroft, 2010, 13), INRIA (Dawar, 2009), Microsoft Research (Hand, 2011, 12, 13), and NICTA (Myreen).

The Laboratory's research groups have made outstanding contributions to the discipline over the REF period. The following are some indicative examples.

Cambridge research makes formal verification of machine code practical, with applications in academia (Mads Dam, Sweden), government (NICTA, Australia; DSTL, UK) and industry (DRisQ, UK; Rockwell Collins, USA) already happening. Advances from Cambridge that made this possible were realistic processor models (Fox), decompilation theory and toolchain (Myreen). The academic quality is demonstrated by Myreen winning the BCS Distinguished Dissertation Competition. The change in the external environment is demonstrated by NICTA stopping trying to verify C implementation of seL4 OS and switching to decompilation using Fox's model of ARM and Myreen's decompilation tools. The £5M EPSRC platform grant in Rigorous Engineering for Mainstream Systems (Sewell) demonstrate the esteem in which Cambridge's research is held, and has provided direct application of theoretical models and theoretically based tools to mainstream industrial problems. Sledgehammer (Paulson) changed the research direction in automated reasoning. It has inspired related work and also the application of techniques, such as machine learning, to extend Sledgehammer itself. MetiTarski (Paulson) appears to be following the same route. For example, it has recently been integrated with both PVS and KeYmaera.

Cambridge chooses to release a lot of its research code as open source. Xen is a key example where the open source release changed the discipline. Other open source releases include NetMaker (S Moore), a network-on-chip simulator which has been used by other institutions; the TigerMIPS processor (S Moore), originally designed for teaching, which has been used elsewhere, e.g., in the Toronto LegUp high-level synthesis system; the Cam3D corpus and CLM-Z face tracker (Robinson) which have both been made publicly available and are being used by research groups in other universities; and the NetFPGA project (A Moore, with Stanford and others) which now has hundreds of users across institutions worldwide. The Laboratory's research on mobile and social networks (Crowcroft, Mascolo, Yoneki) provided key impetus for the creation of the new top-level ACM Conference on Online Social Networks (COSN). Anderson's work on Security Economics arguably formed the nucleus of a new research field.

Much of the Laboratory's research is informed by industry and is conducted in partnership with industry. The Laboratory collaborates closely with a wide range of companies, many of whom provide research funding. Examples in the period are: ABB (Sweden), ARM (UK), Altera (UK), BAE (UK), *Boeing* (USA), BP (UK), BT (UK), *Cambridge Assessment* (UK), *DRISQ* (UK), *Google* (USA), HP, *Huawei* (China), *IBM* (UK), Intel (USA and EU), *Jane Street Holdings* (US), Kodak, *Marconi*, *Microsoft Research* (UK), *MTK Wireless,* NetApp, Northrop Grumman, Optimax, Panasonic (UK), *Qualcomm*, *Samsung*, Seiko Epson (Japan), *SRI International* (USA), *Thales* (UK), Toshiba Research (UK), Toyota (Japan), and Xilinx (USA). Those in italics are those active at the end of the REF period (31/12/13).

The Laboratory runs an Industrial Supporters' Club that has 68 corporate members (at 20/11/13). This is a mix of local, national and international businesses, including most of the companies listed above, which actively support teaching or research in the Laboratory. Members collaborate with the Laboratory's researchers, and contribute funds toward PhD studentships. The Club runs an annual recruitment fair for undergraduate and postgraduate students, which currently has more

companies wanting to attend than there are finalists wanting jobs.

More distinctively, the Computer Laboratory continues to be an important micro-engine of wealth creation in the UK. The RAE2008 Computer Science and Informatics sub-panel singled out for comment the Laboratory's "impact on industry that results from a strong 'spinout culture'." Its staff and alumni have so far created more than 200 companies. Amongst recent spinouts are Bromium (computer security, 2010), Fuse Pump (e-commerce, 2009), GeoSpock (mobile apps, 2013), Globosense (home security, 2009), Green Custard (software consultancy, 2009), Rapportive (business networking, 2010), and the Raspberry Pi Foundation (education charity, 2008).

Cambridge has a very high concentration of technology companies, known colloquially as "the Cambridge Phenomenon" or "Silicon Fen." Engagement with the Cambridge Phenomenon has produced collaborative relationships with some exceptional spin-out companies, many of which originally grew out of Laboratory research and which now feed back into the Laboratory's research environment. Examples of interaction and collaboration with Cambridge Phenomenon companies include work with the Raspberry Pi Foundation (Mullins, Mycroft), ARM (Jones, Sewell), Brady PLC (Anderson), Bromium (Madhavapeddy), Cambridge Assessment (Briscoe), Cambridge Consultants (Blackwell), Cronto (Murdoch), Linguamatics (Copestake), RealVNC (Hopper), SolarFlare (Hopper, A Moore, Rice), Ubisense (Hopper) and XenSource (Bacon, Hand).

The Cambridge Computer Lab Ring, the Laboratory's graduate association, keeps the Laboratory in contact with over 600 members, the majority working in industry. The Ring is an important resource for entrepreneurial students, as it acts as an effective business club. The Ring awards annual prizes to the company of the year and product of the year (eligibility, in both cases, requires a connection to the Laboratory), and to the research publication of the year from the Laboratory. The six "company of the year" awards in the REF period went to Raspberry Pi, Trampoline Systems, RealVNC, Ubisense, Linguamatics, and XenSource.

Consultancy and professional services

All academic staff are free to undertake consultancy work. This is seen as a way of enhancing their experience of industrial problems and of transferring knowledge to industry and government. Some work is done *pro bono*, such as some consultancy for HM Government. Paid consultancy may be done through Cambridge University Technical Services (CUTS) or privately, as the staff member chooses. CUTS provides an excellent service that includes contract negotiation, invoicing, and professional liability insurance. Since 2008, Laboratory staff have carried out consultancy work for many companies, including (as indicative examples) Alcatel (Bell Labs), Apple, AOL, BBC, BT, CSR, France Telecom, Google, Intel, Juniper Networks, Microsoft, Netronome, and Orange.

Anderson, Blackwell, Clayton, Dodgson, Hand, Madhavapeddy, A. Moore, Murdoch, Mycroft and Robinson have all been retained as expert witnesses in various legal cases.

Laboratory staff also serve on or have provided evidence to various advisory panels, including:
- TSB Emerging Technologies and Industries Steering Group (Hopper as Chair)
- Science and Technology Committee of the House of Lords (Clayton)
- Commons Science and Technology Select Committee (Clayton, Daugman)
- Commons Select Committee on Scientific Advice and Evidence in Emergencies (Anderson)
- Joint Select Committee on the Draft Communications Data Bill (Anderson, Murdoch)
- Blackett Review of Cybersecurity (Anderson)
- All Party Parliamentary Communications Group (Clayton)
- Lifeboat Foundation Scientific Advisory Board (Holden)
- UK Computing Research Committee (Pitts)
- EPSRC ICT Strategic Advisory Team (Pitts)
- EPSRC Peer College (Bacon, Blackwell, Briscoe, Crowcroft, Dawar, Gordon, Jamnik, Mascolo, A Moore, S Moore, Murdoch, Paulson, Pitts, Robinson, Sewell, Teufel)
- EPSRC Early Careers Focus Group (Rice)
- Royal Society's International Exchanges Committee (Murdoch)

Since 2008 members of the Laboratory have delivered over 160 invited and keynote lectures. Notable examples include:

IET President's Address: Hopper (2012)
IET Prestige Lecture: Anderson (2010)

BCS Computer Journal invited Lecture: Crowcroft (2010)
Annual BCS Lovelace Lecture: Copestake (2008)

Amongst the most sought-after speakers are: Hopper (many dozens of lectures during his presidency of the IET), Anderson (24 invited lectures), Blackwell (16), Stajano (16), Mascolo (11), Briscoe (9), Crowcroft (9), Staton (8), Dodgson (6), Robinson (6), Sewell (6), Daugman (6).

Since 2008, Laboratory staff have been involved in editing around 40 different journals, including: ACM Transactions on Computational Logic (Dawar), CACM Research Highlights (Crowcroft), Computational Linguistics (Clark), Computer Graphics Forum (Dodgson), Computer Speech and Language (Briscoe, Clark), Foundations and Trends in Programming Languages (Pitts), IEEE Computer (Bacon), IEEE Transactions on Dependable and Secure Computing (Stajano), IEEE Transactions on Mobile Computing (Mascolo), Journal of Automated Reasoning (Paulson), Journal of Formalized Reasoning (Sewell), Journal of Visual Languages and Computing (Blackwell), Journal of Natural Language Engineering (Clark, Teufel), The Computer Journal (Robinson).

Laboratory staff have served as programme chair or co-chair for 38 conferences during the REF period including these top-level conferences: ACM **EuroSys** (Hand, 2008), ACM/IFIP/USENIX Int. Conference on **Middleware** (Bacon, 2009; Mascolo, 2010), Association for Computational Linguistics (**ACL**) (Teufel 2008; Clark, 2010), BCS Conference on Human-Computer Interaction (**HCI**) (Blackwell, 2008), IEEE Conference on Computer Communications (**Infocom**) (Crowcroft, 2009), IEEE International Conference on Pervasive Computing and Communications (**Percom**) (Mascolo, 2011), IEEE International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (**MASCOTS**) (Rice, 2011), IEEE Symposium on Logic in Computer Science (**LICS**) (Pitts, 2009), Interactive Theorem Proving (**ITP**) (Paulson, 2010), International Colloquium on Automata, Languages and Programming (**ICALP**) (Pitts, 2012).

Laboratory staff have served on the programme committees of hundreds of conferences.

Leadership of professional associations

IET (Institution of Engineering and Technology): Hopper vice president (2010–12), president (2012–13)
Royal Society: Hopper member of council (2009–11)
Royal Academy of Engineering: Hopper member of council (2007–10).
European Association for Logic, Language and Information (FoLLI), Copestake elected President, (2012-14)
European Chapter of the Association for Computational Linguistics (EACL): Clark elected chair (2013-15), chair elect (2011-13)
European Association for Computer Science Logic (EACSL): Dawar elected President (2013-17)
European Association of Programming Languages and Systems (EAPLS): Mycroft co-founder and board member (2006-10)
IEEE: Bacon member of Fellowship Committee (2008), of CS Fellowship Committee(2012, 13)
FreeBSD Foundation: Watson president (2008-12), board of directors (2003 onwards)

Honours and fellowships

Honours: Hopper (**CBE**, 2007), Daugman (**OBE**, 2000)

FRS: Gordon (1994), Hopper (2006), Anderson (2009), Crowcroft (2013)
FREng: Hopper (1996), Crowcroft (1999), Anderson (2009), Leslie (2010)

FACM: Crowcroft (2002) , Paulson (2008), Pitts (2012)
FIEEE: Bacon, Crowcroft
FIET: Hopper (president 2012–13), Anderson, Crowcroft, Dodgson, S Moore
FBCS: Bacon, Crowcroft, S Moore, Pitts, Robinson
FIMA: Anderson, Daugman, Dodgson, Gibbens

ACM SIGCOMM Award for Lifetime achievement: Crowcroft (2009)

RAEng McRobert Award (the premier award for UK innovation in engineering): Hopper (2013)

Honorary doctorates: Hopper (Queen's University Belfast, 2010), Bacon (Open University, 2013)