Institution: University of Cambridge, Department of Computer Science and Technology
Unit of Assessment: 11
1. Unit context and structure, research and impact strategy

1.1 Context

This Unit of Assessment is essentially the Department of Computer Science and Technology – a world-class research facility combining theory with practical activities, and significantly advancing both the field and computing in the wider world. The Department sustains active research across the breadth of computer science and encourages the development of new technologies and applications.

Key elements of the Department's ethos are our focus on impact, and openness to working closely with both academic and non-academic organisations. Our activities are formally overseen by the Faculty Board and the Degree Committee (whose Chair and some members are external to the Department.)

The Department occupies a single purpose-built facility. We strive to be a single coherent community with an open environment where all academics, research staff and students can contribute to discussion of topics affecting the Department. Over 260 people are engaged in research here. On the census date, the Department employed 54 permanent academic[1] staff – an increase of 13 since the last REF – and 110 contract research staff (an increase of 26), and also accommodated 3 research fellows funded by colleges and other agencies. Sixty of the research staff were employed on HESA Category A contracts, and 28 of these were identified as independent researchers.

We've been able to attract a large pool of excellent candidates for new positions, even in highly competitive areas – e.g., receiving 128 applications for a Lecturer/Senior Lecturer position in Machine Learning and subsequently being able to appoint three new staff. Several new appointees have joined from industry (see section §1.4). The new permanent staff include seven women and gender balance in this period has improved at all levels (see §2.4).

PhD student numbers are at 100 and increasing rapidly, with over 50 new students in the academic year 2020-21 (see §2.3). These figures reflect a strong increase in research funding coming from more diverse sources (see §3.1). As discussed below, and in §1.3.3, an increasing proportion of our research is interdisciplinary.

One notable strength is the Department's range of highly impactful long-term research projects such as CHERI*[2], a 10-year processor architecture security technology project that is now at the centre of the £187 million Digital Security by Design cybersecurity programme with investment from the UK government and major industrial players. Another is the diversity of pathways to impact (see §1.4.) from spin-outs (e.g., from the Unikernels* research) to online learning platforms (e.g., Isaac*) to Iris recognition* technology being incorporated into international standards and used by international government agencies during its global deployment.

1.2 Structure

We classify research undertaken here by *themes* – i.e., research specialisms – and application areas like 'Education' and 'Health', which involve collaborations between researchers from this Department and other disciplines and/or external organisations.

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[1] Including Emily Shuckburgh who is a member of this Department but for the purposes of the REF is being returned by UoA 7.
[2] Starred Names* denote impact case studies.

Themes centre on the methodologies and technologies employed in research. They are:

- *Algorithms & Complexity*: application of logic to computational complexity, the design and analysis of algorithms.
- *Computer Architecture*: CPUs, accelerators, interconnect, memory hierarchy, SW/HW co-design.
- *Graphics, Vision & Imaging Science*: interpreting, creating, and animating visual data.
- *Human-Centred Computing*: affective computing, human factors, design, HCI.
- *Machine Learning* (ML) & *Artificial Intelligence* (AI): foundational ML methods, data science.
- *Mobile Systems, Robotics & Automation*: IoT, wearables, robotics, sensors and sensor networks.
- *Natural Language Processing*: computational linguistics, algorithms and machine learning approaches adapted to language and text.
- *Programming Languages, Semantics and Verification*: automated reasoning, compilers, foundations, logic and programme analysis
- *Security*: privacy, security, cryptography, cybercrime.
- *Systems & Networking*: distributed systems, databases, wireless, operating systems, virtualisation.

The Department has significant strengths in all these, but is most notable for its consistent success in bringing researchers from different themes to work together – e.g., in the following application areas where we have large ongoing projects and activities:

- *Security by design*. The REMS* and CHERI* projects involve world-leading expertise from the *Computer Architecture, Programming Languages* and *Security* themes using full hardware-software co-design, as well as formal modelling and proof.
- *Education*. The ALTA Institute (part of the Text prediction and feedback* impact case study) is a product of our work in *Machine Learning* and *Natural Language Processing*. In collaboration with the Department of Engineering, Linguistics and Cambridge Assessment, it is improving educational technology for English language learners.
- *Mathematics* both underlies much of the Department's research and is an important application area. The *Algorithms & Complexity and Programming Languages, Semantics and Verification* themes, in collaboration with the University's Centre for Mathematical Sciences, both use and create new results in mathematical logic and category theory, such as in Glynn Winskel's ERC ECSYM project. Lawrence **Paulson**'s[3] ERC ALEXANDRIA project aims at large-scale formal proof for the working mathematician via modern verification technology, such as the Isabelle/HOL interactive theorem prover.

Themes describe the Department's activities externally. Internally, activities fall within research groups. These provide structure for postdoctoral staff and PhD students – e.g., by organising specialist seminars, and running feedback sessions for draft papers – and influence decisions such as space allocation.

The main changes in research structure during this REF period arose from strategic decisions to build capacity in key areas where computer science has potential for huge societal impact. One is environmental science, long an important area here – as evidenced by 'Computing for the Future of the Planet', Andrew **Hopper**'s 2017 Royal Society Bakerian Prize-winning research initiative.

We made two interdisciplinary appointments in 2019: Emily Shuckburgh from the British Antarctic Survey as Reader in Environmental Data Science and Srinivasan **Keshav** as Robert Sansom Professor of Computer Science, to work broadly on using computer science techniques and technologies to encourage the adoption of renewable energy and combat climate change. Shuckburgh is Director of Cambridge Zero, the University's climate change initiative, and PI and Co-Director of AI4ER, the Cambridge UKRI Centre for Doctoral Training in the Application of Artificial

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[3] **Names in bold** denote staff we are submitting. We also give their first name on initial mention.

Intelligence to the study of Environmental Risks. **Keshav** and Damon **Wischik** are Deputy Directors of AI4ER.

There has also been concerted expansion in Machine Learning (ML) and Data Science (DS). Significant efforts by both Heads of Department **(Hopper** to May 2018, and then Ann **Copestake)** secured a donation from DeepMind to fund a Chair of Machine Learning. This enabled us to make a key appointment (Neil **Lawrence**), which helped us attract other new staff. Overall, we have recruited six people with expertise in these areas since 2016 (**Wischik**, Shuckburgh, **Lawrence**, Carl Henrik **Ek**, Ferenc **Huszar**, Nicholas **Lane**); five of these are new positions. The new expertise complements the work of existing staff already well established in this area (especially Sean **Holden**, Pietro **Liò**, Mateja **Jamnik** and others).

A particularly strong emerging feature of the Department is the focus on ML/DS as an integral part of computer science, including systems **(Lane**, **Lawrence**), programming (Andrew **Rice**) and computer architecture (Robert **Mullins**). This complements the work of other research groups in the University, particularly the internationally-acclaimed Machine Learning and Machine Intelligence group in Information Engineering, with whom we have strengthened ties through joint involvement in projects.

A major part of our strategy involves collaboration with other disciplines to enhance their research by using cutting-edge ML/DS techniques – as we are doing in a Mark Foundation Institute for Integrated Cancer Medicine initiative involving **Liò** and **Jamnik**, that uses advances in machine learning to integrate diverse breast cancer patient data and derive insights from it. (This is in collaboration with Cambridge University Hospitals Department of Oncology and the University Department of Radiology.)

We recently obtained substantial funding from Schmidt Futures for our new 'Accelerate Programme for Scientific Discovery' to equip researchers with the skills they need to use ML in their research. Similarly, this Department is a hosting partner of AI4ER and eight of the ten inaugural students who started their PhD in 2019 are supervised or co-supervised by academic staff here. Such activities align with another of our strategic recruitment objectives, to increase our interdisciplinary work (see §1.3.3).

1.3 Research Strategy

The Head of Department (HoD), Deputy Heads and Research Strategy Manager have overall responsibility for the strategic development of research, in consultation with the University School of Technology. The process is highly consultative: relevant research-related matters are discussed at weekly term-time staff meetings, involving all REF Category A staff and the more senior professional services staff. There are occasional structured meetings to explore particular issues more widely, and an annual offsite meeting.

1.3.1 Review of research plans described in REF 2014

1. *Expand the academic staff by four over the period 2013-2018*. In fact, we expanded from 41 to 54 staff by the end of the REF period (see §2) in order to maintain a broad range of research and stay internationally competitive, supported by success in obtaining funds, including via the ERC and the Alan Turing Institute.

2. *Expand support functions, particularly the finance office*. This plan was modified because we saw the need to create a broader Research Strategy Team to support all aspects of research, not just financial. (See §1.3.2.)

3. *Start planning towards a new building for 2020 onwards.* This is the only plan not yet to have succeeded, for reasons discussed in §1.3.4.

4. *Smooth out the cluster of 2020 retirements by using reserves to recruit early to some of these posts.* We have increased staff numbers as well as recruiting early.

5. *Further diversify funding and increase industrial engagement.* Our successful diversification and increase in funding is described in §3. Growth in industrial engagement is described in §4.

1.3.2 Strategic planning after REF 2014

To supplement the usual planning processes described above, in September 2018 the Department underwent a Strategic Research Review (SRR) with an external panel, chaired by Marta Kwiatkowska (University of Oxford) and including panellists from Carnegie Mellon University, UCL, the University of Austin at Texas and Nokia Bell Labs. This was purposely timed to take place shortly after **Copestake** took over as HoD. The SRR identified several priorities, including:

- *Communication and Support.* The panel recommended establishing a communications role here – to highlight the Department's successes to funders and society at large and raise the profile of the quality and scope of research here – and recruiting more academic-related staff "to lessen the administrative workload of academic and professional services staff".
- *Culture.* "Carefully manage the impact of any further growth on the Department's internal culture. Foster early collaboration and communication between faculty and PhD students and reflect on the integration process… in order to ensure the satisfaction and well-being of its graduate student population."
- *PhD funding.* The panel suggested we optimise the return from industrial links to fund studentships.

The Communication and Support priorities extended our existing plan 2 (see above) to expand the finance office. This led to the establishment of a Research Strategy Team, headed by the Research Strategy Manager, which currently has five staff (2.8 FTE) and is still growing. Internally the team supports many aspects of grant applications (see §3.3). Externally, its functions include communications, managing an association for industrial supporters – the Supporters' Club – and another for alumni, the Cambridge Ring (see §4.4.). Generally, the SRR made positive comments about Departmental culture, including highlighting the collaboration between groups, and intellectual freedom. Their recommendations about the integration of postgraduate students led us to introduce more structure to student induction (see §2.3).

1.3.3 Interdisciplinary Research

Since the last REF period, we have focused on expanding interdisciplinary activities to help extend the impact of our research. We achieved this through appointing new academic staff who have strong interdisciplinary links or come from different disciplines.

- Paula **Buttery**, a computational linguist, now leads the ALTA Institute, a key demonstration of the importance of the multidisciplinary approach to language learning and assessment.
- Alice **Hutchings** has a background in criminology and is Deputy Director of the Cambridge Cybercrime Centre, which combines expertise from computer science, criminology and law.
- **Keshav**'s conservation focus is discussed above.
- **Lawrence** leads the Accelerate Programme for Scientific Discovery.
- Shuckburgh, a mathematician, climate scientist and Director of Cambridge Zero, leads AI4ER.

- **Wischik** is a mathematical statistician who, prior to joining us, was chief data scientist at Silicon Valley start-up Urban Engines (now part of Google).

The Department greatly benefits from the University's support for interdisciplinary activities via its Strategic Research Initiatives and Networks (SRIs and SRNs) and Interdisciplinary Research Centres (IRCs). These groupings aim to address multidisciplinary research challenges, strengthen collaborations across disciplines, and influence research and policy agendas. **Copestake** co-directs the Cambridge Language Sciences IRC. The Cambridge Global Challenges SRI, co-led by Alan **Blackwell**, promotes research to advance sustainable development goals and works in collaboration with partners in low-income countries. Other SRNs and IRCs with substantial involvement from the Department include CamBridgeSens (sensors) and the Cambridge Centre for Data-Driven Discovery. **Simon Moore** and Jat **Singh** co-chair the Trust & Technology Initiative which was kick-started with University funding.

1.3.4 Future strategic aims

People. Our academic staff numbers have grown rapidly over the last seven years (§2.1) but will not continue expanding at the same rate. As part of the SRR, it was decided we should keep to about 50 academic staff for the next few years. (This still implies recruiting 1-2 academic staff per year as staff retire or leave.) Supported by the University's Equality and Diversity section, we plan to continue increasing our proportion of female and BAME staff. We will also offer several five-year fellowships for postdoctoral researchers with about three years' experience post-PhD. (This gap in current provision results in us losing some of our most promising researchers to industry.) We have already hired four Fellows through the Accelerate Programme for Scientific Discovery. We also aim to further increase the PhD student numbers. These objectives require funding: further philanthropic donations (from industry or foundations) are the most likely source.

Building. Plans drawn up in 2016-17 to extend our current building showed a high cost for a relatively small space gain and so were ruled unfeasible. However, some pressures on space are being relieved by the expansion of the University's West Cambridge site, especially the Shared Facilities Hub (SFH), expected to be completed in 2021-22. The pandemic has probably put a substantial extension/new building beyond financial reach in the near future but has encouraged us to re-examine our use of space. So we are reconfiguring existing spaces to meet needs, e.g., repurposing our library space (since there will be a library in the SFH) as a flexible workshop/teaching area.

Industrial and third-sector collaboration. Some of our most important current projects (e.g., CHERI*) involve multiple companies collaborating with our researchers and each other; we hope to increase this style of interaction. We also wish to support the involvement of third-sector organisations and other disciplines in our research. The Isaac* online platforms and the ALTA Institute are examples of this and form a core for further collaborative research in applications of computer technology in education.

Research areas. We expect further growth in all areas, especially digital security, mobile devices, data science and ML. Increasing the impact of our activities within the University is a strategic aim, particularly through supporting the growth of ML/AI across Cambridge in collaboration with Information Engineering. We see huge potential for further growth in collaborative research in both sciences and humanities – a specific objective is to collaborate with the University's new Centre for Digital Humanities. This also links with our aim to increase our work in education.

Research support. We will further grow our new Research Strategy Team and recruit more project managers and research software engineers.

1.4 Impact Strategy

The 2018 Strategic Research Review noted that "members of the Department have established strong, long-lived links to industry to support and develop ongoing world-leading research and explore new and exciting areas", and "the majority of research done in the Department reaches wider society through government policy, the health sector, industry and charities."

This variety and vitality of impact is facilitated by the University's intellectual property policy – which gives researchers the right to make results public and the ownership of copyright (including copyright in software) – and by University employment contracts that place few restrictions on employees' activities outside the University. This offers researchers significant flexibility to engage in, among others, formal and informal collaborations with companies and third-sector organisations, spin-outs, start-ups, and non-profits.

Our impact case studies reflect this range of paths to impact. Text prediction and feedback* led to a start-up and spin-out, both subsequently acquired by established companies; CHERI* and REMS* involve close collaboration and interchange of researchers with major industrial companies; non-profit company Raspberry Pi* has achieved impact through community-building; the Isaac* online learning platforms do so by public service to education.

Our strategy for sustaining impact is to maintain and develop an impact culture. Our impacts are diverse and individual researchers/groups of researchers are usually best placed to decide how to pursue them – though our Research Strategy Team also supports them, e.g., by suggesting sources of impact/translational funding or through their links with Cambridge Enterprise, the University's commercialisation arm. Impact often requires continued hands-on involvement of academics in translation of research: the University's liberal IP policy facilitates this, as does the Department's willingness to support unpaid leave and other forms of flexible working. Potential for impact is an important factor in hiring and promotion: when hiring researchers, we pay as much (if not more) attention to the impact/potential for impact of their work as we do to the volume of their publications. Interchange of staff and students between academia and industry is also essential and several recently-recruited academic staff have joined us from industry (**Huszar**, Twitter; **Lawrence**, Amazon; Cengiz **Oztireli**, Disney Research Switzerland; **Wischik**, Urban Engines). Researchers are generous in sharing their experience with colleagues, and entrepreneurship (among staff and alumni) is celebrated in the Cambridge Ring. (§4.4).

Since 2019, we have been seeking to amplify our impact successes to raise the Department's profile with prospective funders and collaborators. Ensuring impact is communicated much more widely is part of the new communications role.

The Department's culture is an integral part of the local Cambridge tech environment. Staff and alumni of the Department have so far created 300 companies and the central role the Department played in the Cambridge Phenomenon is well known. This high degree of interrelationship persists and grows. Members of local companies and third-sector organisations interact frequently with members of the Department, collaborating on research and start-ups, co-supervising PhD students, proposing undergraduate/postgraduate projects, giving seminars, acting as members of our Faculty Board and informally advising and being advised. Because of its ubiquity, this is impossible to quantify: as the SRR highlighted, members of the Department experience it as a unique culture and it is a major factor in their choice to come to, and stay in, Cambridge.

1.5 Open Research and Research Integrity

We take full advantage of the University's Open Access support (such as the Apollo repository, guidance on practice and training programmes for open research and open data management and

the Cambridge Open Access policy framework). However, we go well beyond these institutional measures: the right to release material as open source is strongly promoted by the Department through its long standing open culture, embodied in flexibility of collaboration, open source software and hardware outputs in many areas, open innovation practice evident in our impact strategy, and open research in sharing data and publications.

Our open source release of the Xen hypervisor is a notable part of our history; it changed the discipline and flies the flag for the effectiveness of open research. Some more recent open source releases are described in §4.5. The Isaac* platforms are an example where an industry contract demands open source outputs and where the Departmental approach has enabled collaboration and impact. The Cambridge Cybercrime Centre pioneers practice around research data sharing for sensitive and illicit information. Department personnel have been involved with the CRASSH Open IP for Emerging Technologies research network, exploring the frontiers of open IP tech transfer.

The Department supports a culture of research integrity via an ethical review model, informed by current best practice and the institutional Good Research Practice guidelines, and in consultation with other Schools within the University, and fellow universities. All research projects (including final year undergraduate and Masters' projects) go through up to three stages of review:

- Self-assessment, which may lead to
- Departmental review, which may require guidance from a
- Specialist panel.

Our interdisciplinary interactions with humanities, law and social sciences broadens awareness of ethical issues around the Department. We support ethical review of projects from other disciplines when there is a computational angle. The Research Strategy Team plays a role in spotting potential issues at the early proposal stage. Review at proposal stage is encouraged to drive higher quality submissions. The Department works closely with the University's Development, Research Operations and Research Strategy offices to ensure projects are appropriate.

Discussion of methodological and ethical issues is also built into our teaching. Ensuring reproducibility is especially important in research that uses machine learning, and open sharing of datasets and software allows research results to be reproduced by others. More generally, our open research culture plays an important role in research integrity by ensuring that work can be informally, but critically reviewed by others before submission for publication.

2. People

2.1 Staffing strategy

Our strategy for recruiting permanent academic staff reflects our research strategy of sustaining active research across the breadth of computer science while also encouraging work in important new areas. We made 23 appointments between January 2014 and July 2020 (a marked increase on the five appointments in the previous REF period). The appointments were at all levels of seniority – two Professors, one Reader, 11 Senior Lecturers and nine Lecturers – and seven of the 23 new appointees were women. In recruiting, we looked (as we continue to do) for excellent researchers with both relatively broad interests/expertise and the flexibility to adapt, a factor we regard as important given the rapidity with which research in our field moves and the fact that many staff stay with us long-term.

Four new appointees came from industry (see §1.4) and one from a research institute. The remainder came from universities in the US (two), Canada (one), Switzerland (one), other UK institutions (nine) and Cambridge (five). The Department's strong reputation and strategy of empowering academic staff to work on research topics as they see best allows us to recruit and retain exceptionally talented people even in areas of keen academic and commercial competition: our new staff came to us with PhDs from world-leading institutions.

We have a strong record in staff retention: academic staff may choose their own research agendas, and we are also flexible around consultancy work, work outside academics' University commitments and IP ownership, recognising this generates welcome additional income for research staff and aids staff retention.

Contract research staff have increased from 81 to 110. We had five Research Fellows without an underlying permanent position at the census date. Seeking more Fellowships to help the best researchers build up their research profile before undertaking the full demands of a permanent position, we recently introduced Departmental Early-Career Fellowships (DECAFs). We obtained philanthropic funding for the first four as part of the Accelerate Programme.

2.2 Staff development

For all staff, we recognise the importance of training, mentoring, appraisals and promotions; opportunities to work flexibly; support for their wellbeing; and the need to continue improving equality and diversity in the Department.

As the University is a signatory to the Researcher Development Concordat, all staff can access its comprehensive programme of training and professional development. Departmentally, new academic staff are assigned at least one and sometimes two mentors to help them settle in the short term and offer broader career mentoring longer term. The HoD and Departmental Secretary arrange mentors from outside new recruits' research areas, whereas colleagues closer to their specialism monitor and advise them on their programme of research, both through routine informal contact and through the more formal biennial appraisals, which focus positively on support and academic career development. The mentors, alongside the HoD, provide support during the probation period. Other support for new academic staff includes the underwriting of PhD students and start-up funds (unrestricted, but normally used for travel, specialist equipment, etc) from Departmental reserves. New lecturers are given a reduced teaching load, usually joint-teaching one lecture course in their first year.

The HoD annually and proactively identifies academic staff who are ready for promotion (often aided by appraisals and ensuring staff from underrepresented groups are considered). She encourages

them to apply and supports them through the process, e.g., advising on the choice of referees. She or another member of staff with experience of the promotions process will review applicants' promotion paperwork before it is submitted. She discusses steps to improve CVs with those who are not yet ready for promotion and gives detailed feedback in the (rare) cases where an application is unsuccessful.

Evidence of the career development support we offer academic staff is shown in their strong performance in the University's rigorous and competitive annual Senior Academic Promotion process (as part of which, applications are considered by up to three committees: our Faculty Promotions Committee, the School of Technology Promotions Committee and the University's General Board). During this REF period, out of 39 applications, 35 resulted in promotion /approval for promotion – 6 to Senior Lecturer, 15 to Reader (3 of them women) and 14 to Professor (4 of them women) – a success rate of 90%.

Support for postdoctoral researchers

There were 110 contract research staff employed at the census date. In addition to the 22 Research Assistants (most of them also registered for the PhD), there were 88 postdoctoral staff – 67 Research Associates, 17 Senior Research Associates, 2 Principal Research Associates and 2 Research Fellows as well as 3 research fellows funded by colleges.

Institutionally, the University retained its HR Excellence in Research award in 2015 – a recognition of its commitment to improving the working conditions and career development of research staff. It offers additional institutional support for research staff through the Postdoc Academy, the lead organisation for the postdoctoral community, which offers personal and professional development, pastoral and information support. There are also dedicated support programmes for postdoctoral staff at the Careers Service and the Researcher Development Programme, and subsidised staff housing in Eddington (near to the Department) for which many postdocs are eligible.

Departmentally, postdocs make a vital contribution to our research and we work hard to support their continuing development. Postdocs employed on grants are recruited by academic staff with the support of the HR team. Each is 'housed' in a research group (and some in more than one) providing both their academic and social activities. The Department also has a Research Staff Forum – which meets termly, as a platform to assist postdocs - where staff issues such as training, availability of teaching opportunities and improving career progression can be brought for discussion. All main research groups are represented; the Department Secretary, Deputy Director for Postgraduate Education (Researcher Development) and Research Strategy Manager also attend and liaise with the HoD over issues / suggestions that arise.

Contract research staff can apply for promotion from Research Associate (RA) to Senior Research Associate (SRA), which recognises their status as an independent researcher. There were 22 such promotions in this REF period. The appraisal process is important in identifying RAs who could be promoted to SRA and in advising both roles on their career options, academic and otherwise. Promotions are assessed by the Faculty Board. The Department makes information about the promotion procedure available via our intranet, including case studies from previous successful applicants on how they put their case for promotion. SRAs and Research Fellows with independent status are invited to the Department's weekly staff meetings and offsite meetings, along with permanent academic staff, allowing them to play a role in decision-making around research issues.

Some postdoctoral staff are involved in University teaching, including lecturing and supervision of Masters' projects. We aim to make this opportunity more evenly available so all postdoctoral staff wishing to develop their teaching skills – e.g., to help them pursue a career in academia – are supported in doing so.

Fellowships obtained by members of the Department are detailed in §3.1.

Many postdoctoral staff and fellows leaving the Department have gone to permanent academic positions across the world, including at the Universities of Amsterdam, Bristol, Edinburgh, Otago and Oxford, Carnegie Mellon University, IIT Madras, Imperial College London and King's College London. Four obtained permanent positions in the Department during the REF period. Others have gone into industry, including positions at Apple Research, Brit Insurance, Microsoft Research, Ocado, and to start-ups including Anvil and Navenio.

Knowledge exchange and impact

Academic staff are free to undertake consultancy: we recognise that it enhances their experience of industrial realities and problems, while also creating the links between academia and industry that are essential to knowledge exchange and impact. Some work is done pro bono; paid consultancy may be done through Cambridge University Technical Services (CUTS), or privately, as staff choose. Recently staff have consulted for, among others, Alcatel (Bell Labs), Apple, AOL, BBC, BT, CSR, France Telecom, Google, Intel, Juniper Networks, Microsoft, Netronome, and Orange.

Academic staff are able – and indeed, expected – to take sabbatical leave one term in every seven. They may also take unpaid leave to work with companies. (Though this requires consideration of how to cover their teaching and supervision, it is important both for staff retention and, again, for impact.) Staff may also work for companies alongside their Department positions, as long as it enhances their academic work, for instance by allowing publishable research which would not be possible in an academic setting or by demonstrating impact.

Mechanisms for recognising the impact of work by staff include the Department's annual Hall of Fame awards They celebrate the success of companies founded by Department staff and graduates and successful products these companies create; the philanthropic or social impact of work by staff/graduates; and the most significant peer-reviewed paper by staff/graduates.

2.3 Research students

During the current REF period we admitted 223 PhD students, funded by a mix of Research Council (mainly EPSRC) grants, University resources (e.g., Cambridge Trust, Gates and college scholarships), industrial philanthropy and studentships, project grants, international scholarships and students' self-funding. Thanks mainly to an increase in industrial philanthropy, and the Department's increased involvement with CDTs, student numbers are rising – as shown below.
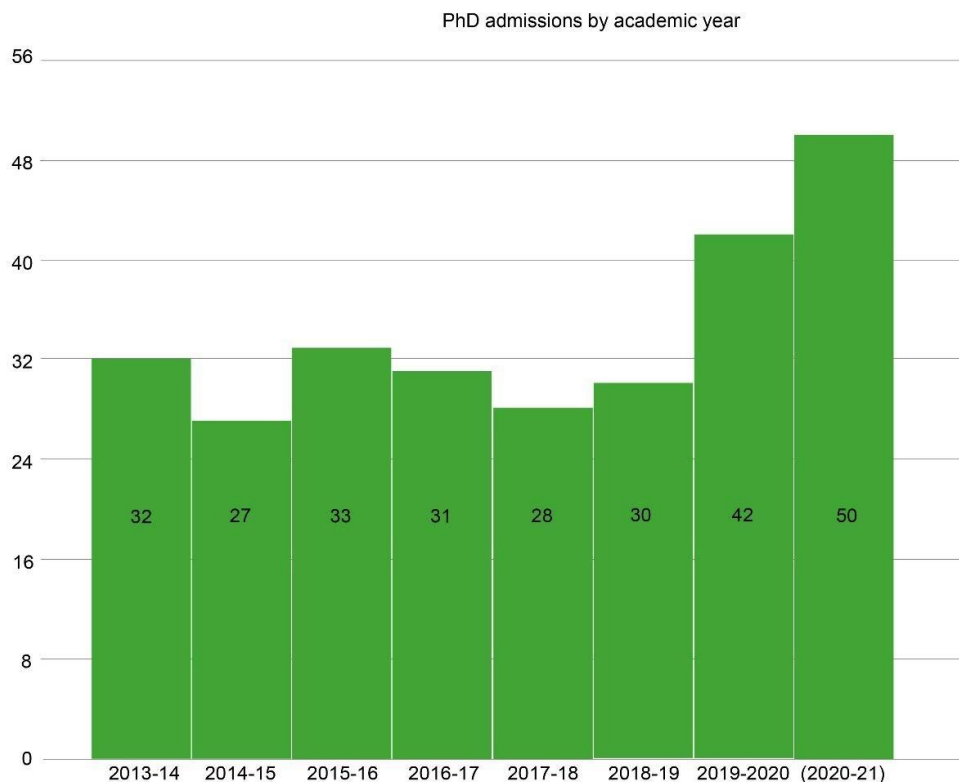
PhD admissions by academic year

Figure 1: PhD admissions by academic year.

Reflecting our increased emphasis on interdisciplinarity, and our increased capacity in AI/ML/robotics, the Department is involved with the following CDTs:

- Sensor Technologies for a Healthy and Sustainable Future (SensorCDT)
- Application of Artificial Intelligence to the study of Environmental Risks (AI4ER).
- AgriFood Robotics (AgriFoRwArdS)

Admission to our PhD programme is highly competitive, our application process and training programme both support rigour; as a result, standards are very high. Students won British Computer Science Distinguished Dissertation Awards in 2015 and 2017; two more were runners-up in 2020.

Recruitment

The PhD application process is designed to combine rigour with support for unconventional backgrounds and diverse candidates – in the last five years, we have admitted students from Psychology, Earth Sciences and Land Economy as well as Mathematics, Engineering and Computer Science.

Typically, about 40% of research students have taken either our one-year MPhil in Advanced Computer Science or the optional fourth year of the undergraduate Computer Science Tripos. These degrees are formally PGT but are intended to prepare students to start research, offering sessions on key skills from research publication to specific research methods, as well as modules on cutting-edge topics in Computer Science and Technology. The vast majority of the other PhD students admitted have undertaken Masters' level training elsewhere, but we also admit students directly from industry, and a Masters' is not a requirement for those with industry experience. Most such students have completed an undergraduate degree in Computer Science or Engineering before entering industry, but we have also admitted PhD students with incomplete undergraduate degrees who were recognised in industry as leading researchers. The students admitted in the last five years – 1 female,

2 male – took some study from our MPhil, or some Open University classes, in their first year to ensure they were up to the academic rigour of a PhD.

Monitoring and support

We implemented the 2018 Strategic Research Review recommendation to introduce more structure to postgraduate student induction. Spread over two weeks, this now includes mandatory completion of several core units on researcher development including soft skills (presentations, confidence building), and better integration into the research groups from the outset. There are also sessions on career development, the help available from the counselling services, and Departmental IT support.

Each student works closely with a supervisor and contributes to the work of a research group, collaborating with others as appropriate. PhD students are assigned both a primary supervisor and a separate graduate advisor who, along with the postgraduate student administrator, is available to discuss problems. Institutionally, PhD students are supported by the wider University and their college (e.g., with financial aid, housing, counselling, etc). All research students have access to necessary online resources and extensive computing facilities, as well as social spaces (café and common room) and events. For female and non-binary students, the women@CL initiative offers a mentoring scheme and online forum for advice on topics ranging from the PhD journey and scholarship funding to 'imposter' syndrome.

The PhD programme includes formal assessments at the end of each year. Students have a viva at the end of the first year, including a report on their progress and research proposal, to demonstrate they are likely to proceed successfully. The second-year report is expected to include detailed plans for completion of the PhD. A third-year progress statement – including either a draft of their dissertation or a plan for finishing it – is considered by the Director of Postgraduate Education.

Skills development and career preparation

Research groups offer students opportunities to develop their skills, e.g., by contributing to weekly seminars or practising their presentations of workshop/conference papers. PhD students are encouraged to submit papers to, and attend, international workshops to make contacts. The Department has funding to support this when other sources are unavailable.

Researcher development is integrated into the first year of PhD study with a compulsory module on the underlying skills required for research, including designing experiments, analysing experimental results, and research ethics. In subsequent years, PhD students are offered a programme of further training, including a range of teaching and research-related courses from the University's personal and professional development staff. Researcher development activity is evaluated and refined in consultation with students by way of the Postgraduate Students' Forum (a Departmental committee formed of student representatives chaired by the Deputy Director of Postgraduate Education (Researcher Development)).

2.4 Equality and Diversity

Recruiting the best people and ensuring the department is a friendly and supportive place to work for everyone is central to our strategy. Our HoD, as she wrote in our 2018 Athena SWAN submission, has herself experienced "the insidious effects of being a woman in a male-dominated subject" and leads the Department in its commitment to addressing equality and diversity. Institutionally, the University supports diversity through a range of initiatives and offers networks for staff and students such as the LGBTQ+ Staff network, the BAME Staff Network and SPACE (for those with caring responsibilities). In recruitment, diversity is explicitly monitored by the University's HR team.

The Department holds an Athena SWAN Bronze award (first received in 2015, renewed in 2018) and made great progress between those dates, including doubling the number of female academic staff. The Department's Equality & Diversity Committee prepares the submission and implements the action plan. Its members represent all staff groups and roles, a range of circumstances (UK/international, different caring responsibilities, etc), and Departmental initiatives such as women@CL (see below). The Department has regularly surveyed staff and students to learn their views about the challenges they face. Actions include ensuring meetings are timed to be compatible with caring/childcare responsibilities and increasing mentoring for postdoctoral staff.

All members of staff – and most PhD students – are required to take the University's Equality & Diversity and Implicit Bias training. This is explicitly checked before they take part in any promotion, recruitment, or supervision activity.

Women@CL exists to support women in computing science in their careers and help them aspire to leadership positions. It is directed by a committee of postdocs and students, with a member of academic staff as liaison; the Department provides administrative support and core funding. Women@CL runs networking events and raises the visibility of female role-models with talks where women academics discuss their research. It runs local career development workshops and (with Oxford University) the Oxbridge Women in Computer Science conference (open to everyone in STEM, regardless of gender identity).

Hutchings founded a Departmental LGBTQ+@CL network in 2018, offering meetings and resources. One postdoc described it recently as "a really welcome link to the queer community at the Lab," adding: "Cambridge lacks any dedicated LGBTQ bars or cafes, and much of the local community is concentrated around the colleges – so for postdocs who are not affiliated to colleges, this can lead to feeling cut off from potential community, support networks, etc. The LGBTQ+@CL initiative is really good, particularly as a resource for new starters to get to know people." Institutionally, the University LGBT+ Staff Network provides information and support to staff, helps coordinate diversity events and helps the University to progress equality.

Though we have further to go, the Department is steadily improving its gender balance. Chairs of selection panels have instituted proactive searches for female applicants. The proportion of female academic staff rose from 12% at the last REF to 20% now. There were only two female Professors at the time of the last REF (one of whom retired shortly afterwards); there are now five. At the current census date, 24% of the contract researchers were female and 40% of the Fellows. (This has since risen to 55% of Fellows, following the appointment of our Departmental Early Career Fellows.) The proportion of female PhD students during this period has fluctuated between 18% and 27%. As of the start of the year 2020-21, it is 27.2%.

Following an initial gift in 2018-19 from DeepMind to fund three Masters' students from underrepresented backgrounds (female, and/or BAME), a further gift is supporting three more MPhil and two PhD students who started in October 2020. Such philanthropic funding is very welcome: it aids our efforts to increase diversity in the Department, and we are actively investigating further opportunities with possible donors.

Support for staff and students with disabilities is tailored to their particular needs, with advice from the University's Occupational Health Service (for staff) and the Disability Resource Centre (mainly for students, although some resources are also helpful for staff).

Leave, wellbeing and flexible working policies

The Department allows academic staff to organise their own time, giving parents/carers freedom to organise their work around their caring responsibilities. We are also flexible in how formally-specified hours and days of work are handled. In practice, most computer scientists require little specialist equipment so remote working/working from home is commonplace. Where there is need, we will supply equipment for home working – including any equipment needed to support staff with disabilities, or problems such as RSI – some of which can be purchased with grant money. (During

the pandemic, we have supplied office chairs, standing desks and equipment for recording lectures to staff.) While most Departmental staff except those whose job requires them to be there at fixed hours (e.g., Reception staff) choose to work full-time, around 11% work part-time (16 female, 13 male).

The University has considerably more generous maternity/paternity/adoption leave provision than required by law. Its graduated return to work policy allows staff to return to work for a minimum of 20% of full-time hours. To support that, we provide breastfeeding and milk refrigeration facilities. Additionally, we offer a range of flexible working options: part-time/term-time working, job share, compressed or annual hours, flexitime, or staggered hours. The Department also underwrites funding for contracts of research staff whose contracts would otherwise finish during their period of parental leave.

The Department encourages researchers to use the Institutional Returning Carers' Scheme, which funds and supports return to work and professional development following a career break or leave for caring responsibilities. Since 2013, four Department members have used this scheme (Laura **Rime**ll, Mateja **Jamnik**, Noa **Zilberman**, Poonam **Yadav**). We are located near two University Workplace Nurseries (West Cambridge and Eddington) and benefit from institutional services such as a salary exchange scheme to support childcare costs.

The University Counselling Service is available to staff and students: it is expected that counselling services will be available in the new West Cambridge Shared Facilities Hub which is very close to the Department.

The Department provides a range of social/wellbeing opportunities to promote interactions between staff and students, e.g., weekly 'Happy Hour' gatherings run by postdocs and PhD students and open to all. We have two Wellbeing Advocates. In 2019, they established a committee to formalise their remit and more effectively promote wellbeing among staff and research students. The committee signposts University initiatives (e.g., its Festival of Wellbeing), promotes Departmental ones, and works with the Department's HR Manager to improve staff processes.

Equality and Diversity in the context of the REF submission

The working methods document for the Unit of Assessment includes a section on how its committee handled Equality & Diversity (paragraph 13). This was checked by the University's REF secretariat and found to conform to the University's policies which themselves have been approved by the national REF authorities.

All members of the committee handling the submission for the Unit of Assessment took the University's training course on Equality & Diversity Essentials and on Understanding Unconscious/Implicit Bias. A further course on Equality & Diversity for REF2021 was taken by the Chairman, the Lead for Equality & Diversity, and the Administrator.

The Department's criteria for promotion to Senior Research Associate reflect the REF2021 indicators of research independence, so identifying staff with significant responsibility for research was straightforward. Discretion was only required for determining the independent status of Research Associates who would be eligible for promotion to Senior Research Associate were funding available. These were resolved in consultation with the Principal Investigators on whose projects they were employed. The affected staff were individually contacted to inform them of these decisions, and none of the decisions were challenged.

All eligible staff were invited to nominate outputs for inclusion in the submission. These were independently assessed for their originality, rigour, and significance. Outputs were then selected for submission so as to best reflect research quality in the Department while complying with the REF requirements for the number of outputs from each member of staff and the overall number of outputs.

Staff were notified of the selection, invited to comment and the selection refined in the light of their responses. Again, none of the decisions have been challenged.

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3. Income, infrastructure and facilities

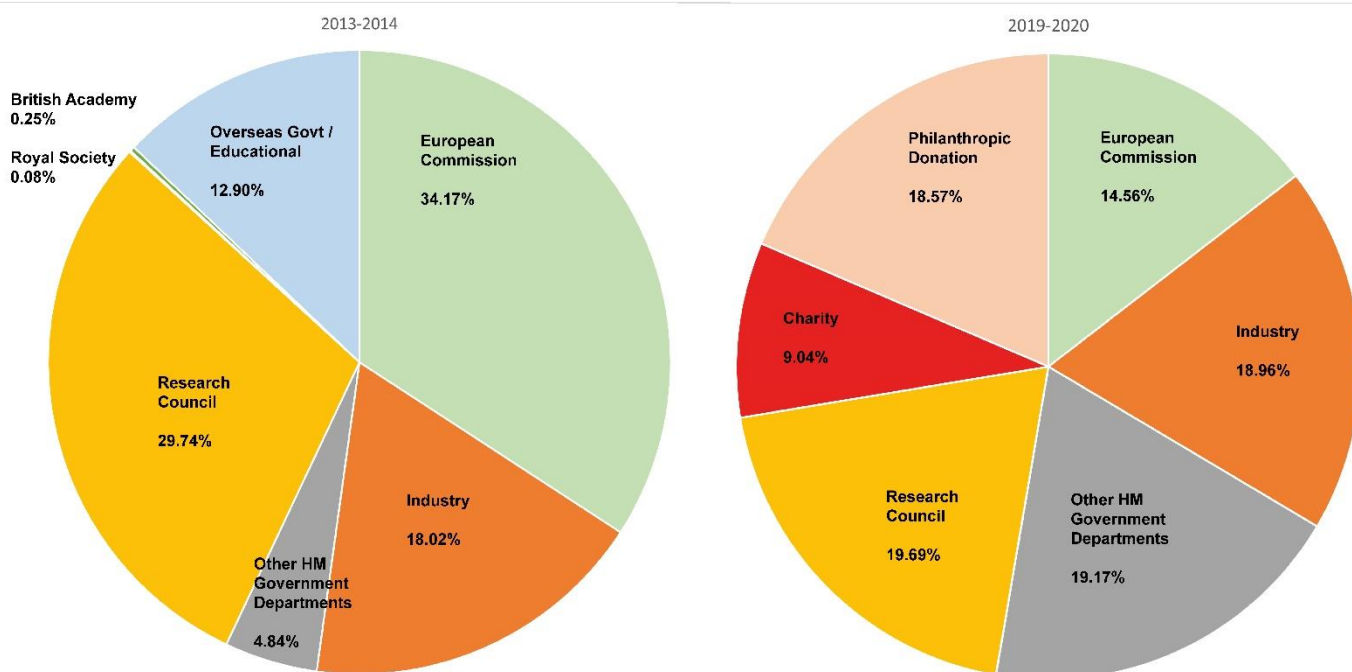# 3.1 Research funding and strategies for generating income

Figure 2: Charts showing comparison of funding sources in 2013-14 and 2019-20, by percentage of total value of awards received.

The Department made the strategic decision in 2010 to diversify its portfolio of research funders and generate research income by combining public funding with industrial sponsorship and philanthropic gifts. Figure 2 (above) shows a comparison of funding sources in 2013-14 and 2019-20, illustrating how continuing that strategy has worked well; increasing proportions of our research income now derive from the third sector, industry and philanthropy.

Philanthropic funding from industry is particularly valuable because it can be used to balance other sources. It has enabled us to admit 20 more PhD students in the last two years and allows us to bridge short gaps between research grants for contract researchers. Where research contracts may be shorter-term and focus on delivery of specific outcomes, philanthropic gifts free us to pursue higher-level goals and help us maintain longer-term academic vision and drive. Our success in obtaining substantial and sustained philanthropic donations (e.g., from Nokia Bell Labs and Qualcomm) is thanks to a combination of highly proactive engagement by successive HoDs and other staff, the excellence of the University's Development Office, and our reputation for advancing the field.

We obtain public funding through responsive-mode applications to UKRI and the ERC via responses to specific calls and through personal fellowships. Alongside public funding, we have obtained funding from UK government departments (e.g., Digital, Culture, Media, and Sport), charities (e.g., The Leverhulme Trust) and industry (e.g., AstraZeneca, Cambridge Assessment, Facebook, Google, and GSK). This period has also seen a considerable increase in funding from overseas government sources. This Department is one of very few UK institutions to receive funding from DARPA, and this is due to the strong relationship between the Computer Architecture Group (**Simon Moore**, Robert **Watson**) and SRI International.

We anticipate this heterogeneity of funding continuing as we proceed with projects across a large number of different disciplines. Beyond the constraint of ethical due diligence, academic staff are free to choose their research direction and the funding sources they approach.

Our success in obtaining funding is additionally helped by our Departmental Research Strategy Team and Finance Office (as described in §3.3), and institutionally by the University's Research Operations Office and Development Office, with whom we liaise closely. New funders in this period include Alcatel-Lucent Technologies, Autonomous Surface Vehicles, Cabinet Office, Cambridge Consultants, DeepMind Technologies, Hewlett Packard Enterprise Company, Input Output HK, Nokia UK, Orange, Raspberry Pi Foundation and Thales UK.

During the current REF period we have obtained substantial industrial funding for major initiatives:

- The ALTA Institute received £2.8M from Cambridge Assessment to conduct research into improving the linguistic proficiency of learners and automated forms of assessment of language performance. (Ted **Briscoe**, Paula **Buttery**)
- The Centre for Mobile Wearable Systems and Augmented Intelligence is funded by a £1.75M donation from Nokia Bell Labs over five years to explore how to augment and improve the human experience in a digitally connected world. (Cecilia **Mascolo**, Alastair **Beresford**)
- The work on OCaml Labs was funded during the period by Jane Street (£4.5M), with other supplementary industry funding. It develops and promotes the OCaml functional programming language as an open-source platform that can be used widely by both industry and academia. (Anil **Madhavapeddy**, Jeremy **Yallop**).
- Huawei has given a donation to support PhD students over five years.
- The Accelerate Programme for Scientific Discovery includes funding from Schmidt Futures for four new Departmental Early-Career Academic Fellows. Additionally, the funding will support six PhD students and six postdoctoral research fellowships.
- Donations from ARM and DeepMind Technologies support work in computer architecture and trustworthy systems engineering.
- Additional funds have come from Microsoft for the Cloud Computing Research Centre in collaboration with Queen Mary University of London. (Jon **Crowcroft**).

The Department is also proud of the number of academic staff who obtain grants from the European Research Council (ERC) via its internationally competitive process. In this period, nine ERC grants were awarded to staff. They were made at all three levels and across a wide range of research projects, underlining the breadth and excellence of the research being conducted here by academic staff at all career stages:

- ERC Starting Grant (Thomas **Sauerwald**, 2015; Nic **Lane**, 2019; Alice **Hutchings**, 2020; Amanda **Prorok**, 2020)
- ERC Consolidator Grant (Rafal **Mantiuk**, 2017; Andreas **Vlachos**, 2019)
- ERC Advanced Grant (Larry **Paulson**, 2016; Peter **Sewell**, 2017; Cecilia **Mascolo**, 2019)

These grantees were in addition to four existing ERC grant recipients (Advanced Grant, Glynn **Winskel**, 2011; Starting Grants, Stephen **Clark**, Rob **Mullins**, Frank **Stajano**, 2012) whose work has enriched our research environment.

Other significant grant awards made by external bodies on a competitive basis include the following EPSRC Fellowships:

- Early Career Digital Economy Fellowship (Jat **Singh**, 2017)
- Early Career Fellowship (Hatice **Gunes**, 2019)
- Senior Turing AI Fellowship (**Lawrence**, 2019)

We encourage postdoctoral researchers to apply for relevant fellowships. As a Department, we can offer some matched funding for these; the University supports postdocs applying for Leverhulme Fellowships – prestigious post-doctoral awards for researchers near the start of their career – through matched funding from the Isaac Newton Trust. The following fellowships were awarded:

- The Royal Commission for the Exhibition of 1851 (KC **Sivaramakrishnan**, 2015)
- Royal Society University Research Fellowship (Cristina **David**, 2017)
- Leverhulme Early Career Fellowship (Noa **Zilberman**, 2016)
- Leverhulme Early Career Fellowship (Ekaterina **Shutova**, 2015)
- Leverhulme Early Career Fellowship (Franck **Courbon**, 2017)
- Leverhulme Early Career Fellowship (Martin **Kleppmann**, 2019)

The first four listed subsequently went on to faculty positions (IIT Madras, January 2019; Bristol, January 2020; Oxford, January 2020; Amsterdam, February 2018), the last two remain in the Department. Additionally, college stipendiary Junior Research Fellowships, which are highly competitive (generally over 100 applicants per place), were awarded to Heidi **Howard**, Guy **Emerson** and Marwa **Mahmoud**.

3.2 Operational infrastructure

As outlined in §1.3.2, we established a Research Strategy Team in this REF period to improve the way we support researchers at all levels through the research funding lifecycle – as shown here.

Figure 3: Support offered to researchers throughout the research funding lifecycle.

Working with our finance office, the Team leads on research funding and partnerships and liaises with colleagues in the University, industry and the third sector to support research, networking and collaborations.

The Research Strategy Manager promotes prospective funders and collaborators to researchers considering a funding application. She recruits relevant panellists (often including researchers who have previously secured the same grant / fellowship) to run mock interviews. After the funding award, she and the Team assist with knowledge transfer and impact arising from the research, offering researchers support in accessing funding for impact. This has helped the Department achieve a high success rate for its applications to the University EPSRC Impact Accelerate Account. She also works with the Department's Communications Coordinator to raise the profile of the research and its impact to draw the attention of other prospective funders, partners, and beneficiaries. She stays abreast of funding opportunities and policies by attending relevant research council meetings and through links with the University Research Strategy Office. She and the Research Strategy Team work closely with networks / affiliations across the University – in areas including knowledge exchange, funding operations and entrepreneurial support – and beyond, e.g., with sector specific networks such as Agri-techE.

The Department has received funding for several Knowledge Transfer Fellowships to support postdoctoral researchers to spend a year working with an industrial partner to apply the results of an EPSRC-funded research project to that business. Examples include TranscenData (2014), ARM (three fellowships in total during 2016-17), Smart Cambridge (2017) and the Met Office (2018). The Department's Entrepreneur in Residence is also part of the Research Strategy Team and can offer help and advice to researchers when they are looking to commercialise their ideas.

3.3 Use of infrastructure for impact activities

The Department is housed in the William Gates Building – a purpose-built facility providing quiet office space, small group offices for PhD students, workshop and lab facilities, lecture theatres and a networking area. It houses both researchers and visitors and enables us to host symposiums and outreach events, enhancing our external connections and furthering research interaction.

Specialist computing support within the Department is provided by an IT team, in addition to the general support offered by the University Information Services. The team provides support for most aspects of our research provision ranging from purchase through to installation and maintenance of servers, storage, and networking.

The Department's data centre offers a number of specialist facilities for researchers, including a GPU cluster for development of machine learning systems, support for prototyping of novel hardware interconnected by high-speed optical networking, a flexible private cloud providing virtual servers, and a highly-reconfigurable and monitorable 'model data centre' for experimentation on distributed systems and novel network architectures.

Individual groups have additional specialised research equipment pertinent to them, usually purchased through research grants. The University Information Services' High Performance Computing (HPC) clusters are also available to Department members, used in conjunction with Departmental GPU and CPU clusters. The HPC is funded partly (27%) by the Department with the rest (73%) coming from University funds.

The considerable in-house computing and communication systems are enhanced by the extensive network infrastructure provided by the University Information Services; for example, the Department's research has made extensive use of the University's dark fibre network around the city centre.

3.4 Benefits in kind

Beyond our own research software and equipment, our sponsors and collaborators enable us to access unique datasets and industrial equipment and assets that greatly assist our research. These

have included a network simulator from Microsoft, FPGA boards from Xilinx, GPUs from NVIDIA (to enable our network traffic research), specialist software from Broadcom and Xilinx, cloud computing credits from Microsoft and Google or anonymized service usage datasets (such as one from location service company Foursquare Inc, which enabled substantial and unique human urban mobility analysis studies).

> **4. Collaboration and contribution to the research base, economy and society**

4.1 Support for research collaborations

Collaborating with others, and in doing so accelerating the impact of research for all partners involved, has been central to the Department's ethos since Maurice Wilkes and his team built EDSAC in 1949 with the aim of creating a general use computer that could benefit as many researchers as possible. Today the Department collaborates widely: with academia (locally, nationally and internationally), industry, government and third sector organisations.

This is facilitated, as outlined in §1.4, by the freedom academic staff have over the amount and type of collaborations they undertake. Additionally, their connections across the Cambridge research landscape, through the collegiate system and interdisciplinary networks, also aid collaboration. When staff seek to collaborate with external partners, we are deliberately flexible over the models of collaboration.

As described in §3.3, our Research Strategy Manager and her Team play a key role in enabling/supporting collaborations. The Research Strategy Manager proactively seeks out collaborators, is first point of contact for potential industrial / third sector partners who approach the Department; and works to find the best alignment between academic research interests and issues prospective collaborators are looking to solve.

Collaborations keep our research projects grounded and relevant. To facilitate them, we are flexible over allowing visitors from industry / academia to work in the Department for both short and long stays. In this REF period, more than 70 staff between them hosted over 700 visitors including scholars, investors, and industrial partners. The OCaml Labs project calculates that in 10 years it has welcomed over 100 visitors (including industry staff, developers, programmers and academics) to help its work on bringing an elegant and precise functional programming language out of obscurity and encourage its use in industry. This openness to visitors helped turn Cambridge into a hub for the OCaml developer community, which continues to work on the open-source language and further its development.

Researchers from Nokia Bell Labs (which funds The Centre for Mobile Wearable Systems and Augmented Intelligence) have 'Visiting Scholar' status in the Department, giving the company flexible access to our teams, enabling them to discuss ideas with PIs here, and directly recruit interns and researchers from the Department – a valuable benefit to them.

We use various models of collaboration to sustain longer-term research. For example, with one major industry partner we set up a framework agreement, running for five years from November 2019, through which they committed to fund research in this Department (plus a division of another University Department). Because the contract negotiation was carried out as part of the overall framework agreement, rather than on a project-by-project basis, academic staff can apply to the resulting pot of research funding through a lightweight application process that is much more streamlined than for individual industry grants.

Institutionally, the University's liberal approach to IP (§1.4) makes Cambridge a very attractive environment for both researchers and collaborators. Additionally, we benefit from infrastructure provided by the University. About two-thirds of academic staff (and all students) belong to a Cambridge college: these provide extra facilities, including additional funding to support travel and other research costs, and accommodation for visiting academics. This helps us host workshops, visitors, and meetings with collaborators.

The Department also benefits significantly from the University's world-class facilities, such as its copyright library. Several researchers collaborate with the Department of Engineering in photonics and display technology, with Engineering's fabrication facilities vital to that research.

4.2 Academic collaborations

The Department engages in numerous academic collaborations locally, nationally and internationally, often involving partners in a range of disciplines.

Nationally, this Department was a founding member of The Alan Turing Institute, the UK's national institute for data science and artificial intelligence. Several academic staff spend time there (e.g., **Crowcroft** as Chair of the Institute's Programme Committee) and advise Turing PhD students and run Turing projects: **Buttery** has a project around understanding social media and unrest; **Crowcroft** has a project in collaboration with Imperial on providing confidential cloud machine learning platforms, and another with the Bill & Melinda Gates Foundation on Trustworthy Digital Identity. Anuj **Dawar** is contributing to foundational work in logic for data science. **Wischik** works in electrical vehicle charging networks.

We continue to forge new national collaborations. In 2020 we teamed for the first time with the University of Lincoln on a Research England Ceres Agri-Tech project where **Oztireli** works with academic staff on using data science/AI to boost cereal yields.

Internationally, the Department has had eight years' joint funding from DARPA, with SRI as the prime contractor, to research fundamentally more secure computer systems. This work has been led here by **Watson** and **Simon Moore**, with a team of over 20 researchers with a broad range of computer science skills, enabling work on new processor architecture, hardware prototypes, compiler support, operating system porting, and benchmarking of applications. This level of funding has gone beyond anything available through standard EPSRC funding mechanisms and has been critical to enable hiring a team with the required breadth of skills to undertake the research and compete with top universities in the USA. The unusual skills of this team have driven effective industry engagement and unlocked significant government industrial funding, as evidenced in the CHERI* case study.

Local collaborations include establishing with the Department of Engineering – supported by substantial University funding – 'The Observatory for Human-Machine Collaboration' in 2018 for the holistic study of the fundamentals of human-machine interaction by putting human and technological perspectives on an equal footing.

Lio's work on machine learning approaches for the analysis of bio-medical data sets has led to collaborations with the University Departments of Clinical Neurosciences, Haematology, Oncology, Psychiatry, Radiology, and Veterinary Medicine.

Holden has been collaborating with researchers in the Department of Biochemistry since 2012, applying Bayesian inference, probabilistic programming and computational learning theory to drug design and proteomics.

Mascolo, who works with different domains on the application of mobile sensor technology, is currently collaborating with the Department of Clinical Neuroscience on diagnostic methodologies for Alzheimer's disease, and with Psychology on behavioural interventions delivered via mobile devices.

4.3 Developing relationships with key research users

We purposefully seek a diversity of partnerships and funding sources for research projects as this helps them develop and evolve through several funding cycles. We also involve collaborators from

heterogeneous disciplines as bringing a range of perspectives to bear on the research helps keep it relevant. Projects that have built long-lasting platforms are detailed in the REMS*, Text prediction and feedback* and CHERI* case studies. Such long-term programmes mean we can see research through its lifecycle from initial idea, through trial and error, to success, knowledge transfer and impact via a spin-out (as from the Unikernels* research), or adoption by a national priority research programme (as with CHERI* and the UK Digital Security by Design Challenge), or via a government department, as with the Isaac* Learning project and the Department for Education.

Since the last REF, we have demonstrated our ability to build on existing research relationships to develop long-term collaborative partnerships with industry. In several cases, by identifying ideas arising from initial collaborations, discussing them with partners and agreeing milestones and deliverables, we have negotiated larger research contracts with them. Examples include ARM (Timothy **Jones**, **Simon Moore**, Peter **Sewell**), Boeing (**Beresford**), Microsoft Research (Alan **Blackwell**), Google (**Hopper**) and Samsung (**Mullins**).

We also have industrial collaborations with many of the technology spin-outs from this Department or cognate University departments. We have ongoing and productive engagements with (among others) the Raspberry Pi Foundation (**Mullins**, Alan **Mycroft**), Cambridge Assessment (**Briscoe**), SolarFlare (**Hopper**, **Andrew Moore**, **Rice**), and Ubisense (**Hopper**).

Formal collaborations with smaller companies often consist of a joint application for funding to organisations such as Innovate UK. In the last three years, **Briscoe** has had two consecutive Innovate UK projects with All Street, who have just launched their first product, and the outputs of **Gunes**' recent project with 'Sensing Feeling' are currently being commercialised.

4.4 External engagement mechanisms

We sustain engagement with our alumni and their businesses (key users of our research) through our graduate association, the Cambridge Ring. Members can network with us and each other – e.g., to make new contacts in key sectors, share job opportunities and interact with our students by offering student projects. Members are also invited (as are the public) to our keynote research outreach event, the annual Wheeler Lecture. Held virtually for the first time in May 2020 due to the pandemic, it attracted 350 attendees. In 2019, the Research Strategy Team assumed management of the Cambridge Ring and put more membership management structure in place, increased communications with alumni and surveyed them to learn more about how the Ring can benefit them. Membership has since doubled and we anticipate increased engagement with our alumni.

The Research Strategy Team also manages our Supporters Club – another mechanism for engaging with wider audiences. This mixed group of local, national and international businesses, ranging from very small to major multinationals, helps support Departmental research through their financial donations to the Department, and via networking and industrial opportunities. Supporters' Club income is used for purposes including funding early stage research, as bridge funding for postdoctoral researchers, and for outreach activities such as our annual Open Days. Members welcome interaction with the Department, including at the annual dinner where they can network with academic staff and research students.

We also engage with wider communities and publics through publications. Notable books in this period include Martin **Kleppmann**'s *Designing Data-Intensive Applications*, translated into six languages and selling over 100,000 copies. *Java 8 In Action* and *Modern Java in Action*, co-authored by **Mycroft** (with alumnus Raoul-Gabriel Urma and collaborator Mario Fusco), have sold over 30,000 copies.

4.5 Wider contributions to Economy, Society and Response to National and International Priorities

We have a long history of working collaboratively with large open source and open (or licensed) data projects and demonstrating the value of doing so by advancing knowledge, generating academic papers and creating jobs. Examples include an open source silicon venture that was incubated in the Department before spinning out as a non-profit company. In November 2019 it announced OpenTitan, the first open source silicon root of trust, a collaborative engineering project with Google, ETH Zürich, Western Digital and other major corporate partners. Other examples include the Isabelle theorem prover; CamFort; Automerge; the COVID-19 Sounds App; the Cambridge Cybercrime Centre and DELPH-IN (one of the first organisations making open source computational linguistics code and data available). This interest in open code and data has extended to an interest in open models of academic publishing: **Lawrence** is Founder and Series Editor of Proceedings of Machine Learning Research, a highly active journal that now publishes the proceedings of three major ML conferences (UAI, ICML and AISTATS) while being completely free for submitters and with the authors retaining copyright.

The Department is eager to see computer science more deeply integrated into society, and to promote computing for social good. Examples of work here range from Vlachos's project on Automated Verification of Textual Claims to combat the proliferation of misinformation online, to the FEVER (Fact Extraction and VERification) dataset in collaboration with Amazon, and to Giving Voice to Digital Democracies (**Copestake** in collaboration with CRASSH, the University's Centre for Research in the Arts, Social Sciences and Humanities and the Department of Engineering). This looks at ethical issues in speech and language technology such as virtual assistants and machine translation.

The Department is closely involved with Cambridge Global Challenges (CGC); this University Strategic Research Initiative works with partners in developing countries to deliver projects to address challenges there. We have hosted CGC members for some years, **Blackwell** is its Co-Director, and from October 2020 CGC is formally 'housed' in the Department. Department members working on CGC projects include Eiko **Yoneki** on the BugAlert initiative to shift traditional, labour-intensive crop pest detection methods to smart crop monitoring technology. Through CGC, there has also been collaboration with Africa's Voices Foundation, an interdisciplinary humanitarian charity. Department member Dr Luke Church is Senior Advisor there, working alongside social scientists on projects including (in 2020) supporting the Covid-19 public health response in Kenya.

Many Department researchers (including Ross **Anderson**, **Hutchings**, **Lawrence** and **Singh**) are part of the University's Centre for Science and Policy, which brings together public policy professionals and academics to learn from each other and improve the use of evidence and expertise in public policy. During this REF period, 37 members of the Department engaged with Policy Fellows at over 100 meetings. These included workshops on transport and data policy organised by **Mascolo**, and **Crowcroft**'s involvement in the Cambridge University Press Data and Policy journal and a Data for Policy conference. Similarly, the Trust & Technology Initiative – a University-wide programme led by the Department – is a forum for interdisciplinary research exploring the dynamics of trust and distrust in relation to internet technologies, society and power.

Along with Raspberry Pi, we pursue multidisciplinary public engagement. In addition to our successful collaboration with them on the Isaac* Computer Science platform, there is the development of Sonic Pi, the code-based music creation and performance tool. This non-profit spin-out from the Department has substantial international impact, attracting a community of 1.5M coders and being used in music education initiatives in the UK, Africa and Finland.

Many academic staff work in advancing healthcare, e.g., **Lio**, **Jamnik** and **Mascolo** with clinical collaborators to advance the use of systems and machine learning to improve diagnosis and patient care in areas from breast cancer to Alzheimer's disease. Meanwhile, many repurposed their research in 2020 to address the pandemic, including **Crowcroft** and **Yoneki**'s seminal work on digital

contact tracing, **Lio**'s work on machine learning for intensive care patient stay prediction, **Mascolo**'s work on audio-based diagnostics for COVID-19 sounds.

Also responding to the pandemic were academic staff at the interdisciplinary Cambridge Cybercrime Centre. Established in 2015 by Richard **Clayton** with EPSRC funding, it combines expertise from this Department and the University's Institute of Criminology and Faculty of Law and has one of academia's largest data sets on cybercrime, used by over 100 researchers at over 30 universities. The Centre gathered a mass of data on the surge in pandemic- and lockdown-related cybercrime and from July onwards produced weekly briefing papers for policymakers, practitioners and academics.

Establishing the Accelerate Programme for Scientific Discovery in 2020 to speed the use of machine learning by researchers in other disciplines was a key milestone for the Department and underlines our commitment to leverage further impact from research by delivering relevant skills training for researchers. In July 2020, we delivered the inaugural 'Data for Science' programme to PhD students and postdocs in disciplines outside Computer Science (including chemistry, engineering, medicine and psychology), helping them learn to apply data analysis to their own datasets.

4.6 Indicators of wider Influence, contributions and recognition

Several staff from the Department serve/have served as government advisors, including:

- **Hopper** in the government's Innovation Expert Group
- **Jamnik** as Specialist Adviser to the House of Lords Select Committee on Artificial Intelligence
- **Lawrence** as member of the government's AI Council, and on the Committee of the Royal Society DELVE (Data Evaluation and Learning for Viral Epidemics) initiative
- Richard **Mortier** as Advisor to the Department for Digital, Culture, Media & Sport on Internet of Things, and Internet Protocols
- **Anderson** as a member of the UK Cybersecurity Policy Working Group and working with the EU Data Protection Board (EU Commission Data Regulator)

Staff elected as Fellows of the Royal Society:

- **Crowcroft**, 2013
- **Paulson**, 2017

Royal Society Medals:

- Bakerian Medal (**Hopper**, 2017)

Awards:

- British Computer Society Lovelace Medal (**Anderson**, 2015)
- N2 Women Stars in Computer Networking and Communications Award (**Mascolo**, 2016)
- Herbrand Award for Distinguished Contributions to Automated Reasoning (**Paulson**, 2017)
- Google Security and Privacy Research award (**Beresford**, 2018)
- N2 Women Rising Stars in Computer Networking and Communications (**Zilberman**, 2018)
- Alonzo Church Award (Andrew **Pitts**, 2019)
- SIGMOBILE Rockstar Early Career Award (**Lane**, 2020)

Distinguished/Best Paper Awards include:

- **Crowcroft**, **A Moore**, **Watson** at NSDI 2015
- **A Moore** at SIGCOMM 2017

- **Prorok** at DARS 2018
- Robert **Harle** at UbiComp 2018
- **Mascolo** at Ubicomp 2014 and Ubicomp 2019
- **Rice** at OOPSLA 2017 and ICSE 2019
- Neel **Krishnaswami**, **Yallop** at PLDI 2019
- **S Moore**, **Sewell**, Robert **Watson** at ASPLOS 2019
- **Hutchings** at the Symposium of ECrime 2019
- **Krishnaswami** at POPL 2020
- **Madhavapeddy** at ICFP 2020.

'Test of Time' Awards:

- **A Moore** at SIGMETRICS 2015
- **Hopper** at SIGMOBILE 2016
- **Mullins**, **S Moore** at ASP-DAC 2016
- **Sewell** at SIGPLAN 2017
- **Lane** at SenSys 2018
- **Harle** at UbiComp 2018
- Marcelo **Fiore** and **Pitts** (separately) at LICS Symposium 2019
- The NetFPGA project (led by **A Moore**) received the ACM SIGCOMM SOSR System Award in 2019
- Marcus **Kuhn** at IEEE Symposium on Security and Privacy 2020

PhD Student Awards:

The quality of research conducted by our PhD students has been recognised by these awards:

- Bhatty, CPHC/BCS Distinguished Dissertation Award 2015
- Bulat, Women Techmakers (formerly Google Anita Borg) Scholarship 2015
- Dolan, CPHC/BCS Distinguished Dissertation Award 2017
- Kumar, ACM SIGPLAN Doctoral Dissertation Award 2017
- Brouwer, Homerton Santander Award for PhD Research 2017
- D'Silva, N2Women Networking and Communications Rising Star Award 2019; VentureBeat Women in AI Rising Star Award 2019; Royal Bank of Canada Top 25 Canadian Immigrants Youth Award 2019
- Grammenos, Distinguished Paper Award at UbiComp 2019
- **Emerson** and Li, runners up, CPHC/BCS Distinguished Dissertation Competition 2020
- Zhao, Apple Scholarship 2020
- Tailor, Best Paper, WellComp 2020

A number of PhD students/early career researchers have received 'Top Reviewer' awards:

- **Emerson** at ACL18/20;
- Cangea for ICML 2020

Most academics serve on programme and organising committees for journals and conferences and are called upon as keynote speakers. Many are also visiting faculty at other institutions including in this period **Lio** at Padova, **Jamnik** at the Centre for the Future of Intelligence, **Pitts** to Aarhus University, **Mycroft** to IIT Bombay, **Buttery** as Principal Investigator, *Computational Linguistic skills training at Makerere University*, in collaboration with Andrew **Caines** and Marek **Rei**.

Many Department members are fellows of learned societies and professional bodies, including in leadership roles, e.g., **Hopper** as Treasurer and Vice-President of the Royal Society. Fellowships include **Paulson** and **Pitts** at the ACM; **S Moore** at the BCS and IET; John **Daugman** at the US National Academy of Inventors. **Crowcroft**, **Mascolo** and **Pitts** have served as Advisory Board

members for the Max Planck Software Systems Institute. Department members also contribute to the wider academic community through refereeing publications and acting as members of grant-awarding panels (e.g., **Copestake**, **Crowcroft**, **Mascolo**, **Pitts**, **Robinson** have served on ERC Research Grant panels).

Copestake, **Crowcroft**, **Hopper** and **Paulson** have been on Royal Society University Fellowships and Award Committees. (**Paulson** is currently serving on the Milner Award Committee.)

A number of Department academics are editors of journals, including **Lawrence** (Action Editor for the Journal of Machine Learning Research; Series Editor of the Proceedings of Machine Learning Research), **Pitts** (Area Editor for logic and computation for the Journal of the ACM, founding Editor of Forum of Mathematics, Pi and Sigma (CUP) until 2017), and Gem **Stapleton**, Co-Editor-in-Chief of the Journal of Visual Languages and Sentient Systems, and Editorial Board member for the Journal of Visual Languages and Computing.