

Institution: University of Oxford
Unit of Assessment: 11 – Computer Science and Informatics
<p>1. Unit context and structure, research and impact strategy</p> <p>1.1. Overview and unit structure</p> <p>This Unit of Assessment (UoA) comprises the University of Oxford's Department of Computer Science (CS), together with two staff from the Oxford Internet Institute, a multidisciplinary unit focussed on the societal impact of information technology. Oxford CS includes 69 academic faculty, over 100 research staff, and over 250 doctoral students, organised into ten research themes. Our mission is to be an internationally leading centre of research, training, dissemination, and impact facilitation across a broad spectrum of Computer Science, ranging from foundations to challenge-led and interdisciplinary work. In pursuit of this objective, we seek to provide facilities and support that enable world-leading research, attract talented staff and students from around the world, and foster engagement with a diverse range of collaborators and external beneficiaries. Our research environment is highly interdisciplinary, enjoying close collaborative links with Engineering, Mathematics, Physics, and the life sciences. Many of our academic staff are recognised as international leaders, and we play a leading role in national research initiatives, such as the Alan Turing Institute. Our ethos of academic excellence is underpinned by a commitment to supporting all our staff and students to achieve their full potential. The following are key indicators of progress over the period:</p> <p><i>Strengthening our research capability.</i> We have established three new research themes – Artificial Intelligence & Machine Learning, Cyber-Physical Systems, and Human-Centred Computing – and made 16 permanent appointments across the Department, including seven early career researchers (ECRs¹). Compared to REF2014, the number of staff returned here who are on permanent contracts has increased significantly, from 48 to 62.</p> <p><i>Expanding our research pipeline.</i> Over the period, we generated over £74m of external research income. We further received £17m in philanthropic donations, including £10m towards a new building, and £4m for studentships and for a new chair in Artificial Intelligence (AI). Our staff were PI on four Centres for Doctoral Training (CDTs), two programme grants, and 21 personal research fellowships (predominantly ERC, EPSRC, and Royal Society). Applications to the doctoral programme grew by 22% a year on average, and we awarded 242 doctoral degrees, compared to 124 for the REF2014 period.</p> <p><i>Facilitating and realising impact.</i> The period has seen a high volume of translational activity, often emerging from large, multi-stakeholder research grants, collaborations with industry, and engagement with policy-makers. Our staff filed 27 priority patents and undertook 122 personal consultancy agreements with 59 different companies. 21 commercial licence deals were agreed with companies in diverse sectors including pharmaceuticals, healthcare, electronics, and manufacturing. Our spinouts raised over US\$70m in investment, and several were acquired by major international companies including GitHub, Meltwater, and Waymo.</p> <p>1.2. Research theme development</p> <p>We have undertaken a major reorganisation of our research themes in pursuit of the research strategy described in REF2014. A key development has been the establishment of three new</p>

¹ REF2021 definition here and throughout.

themes: Artificial Intelligence & Machine Learning (AI&ML), Cyber-Physical Systems (CPS), and Human-Centred Computing (HCC). Here we give an overview of each theme, highlighting advances since REF2014:

Algorithms and Complexity (Head: L. Goldberg; 8 faculty). This theme was created in the previous REF period with the hiring of L. Goldberg, P. Goldberg, Koutsoupias, and Živný to join with Jeavons. Over the current period, the theme has been strengthened with the hiring of Galanis (an ECR) and Santhanam. Research focusses on computational economics, game theory, constraint satisfaction, computational counting, circuit complexity, and randomised algorithms.

Artificial Intelligence and Machine Learning (Head: Wooldridge; 8 faculty). AI&ML is a new, distinct theme combining Blunsom, Calinescu, Elkind, Lukaszewicz, and Wooldridge with new hires Gal (ECR), Kanade, and Whiteson. The theme benefits from expertise across a broad spectrum of AI methodologies, including symbolic AI, multi-agent systems, game theory, Bayesian reasoning, reinforcement learning, and deep learning.

Automated Verification (Head: Kwiatkowska; 9 faculty). This theme is one of the world's largest centres for automated verification and has benefitted from Cardelli moving to a 100% FTE post. Members investigate the theory and practice of automated formal verification and correct-by-construction synthesis for software and hardware systems in diverse settings, as required by modern ubiquitous computing systems. The theme is also pioneering applications of verification to systems biology, machine learning, and dynamical systems.

Computational Biology and Health Informatics (Head: Rodriguez; 9 faculty). The theme engages in computational approaches to biomedical and healthcare research, including multiscale modelling and simulation, image and signal analysis, and semantics-driven technologies. Research aims at improving the efficacy of clinical diagnosis and therapy for cardiovascular, lung, bone, and cancer diseases, and builds on strong collaborations with clinicians, industry, and regulators. The theme supplies the PIs for two CDTs: *Health Data Science* (Davies), offered in conjunction with Oxford's Big Data Institute, and *Sustainable Approaches to Biomedical Sciences: Responsible and Reproducible Research (SABS:R³)* (Gavaghan). With the hiring of Bueno-Orovio (ECR), the theme has enhanced its expertise in data-driven cardiac modelling and simulation.

Cyber-Physical Systems (Head: Trigoni; 4 faculty). CPS is a new theme built up through the hiring of Rogers and Vu to join Trigoni and Markham. Research focusses on intelligent and autonomous sensor systems, with applications in positioning, healthcare, the smart grid, environmental monitoring, citizen science platforms, and smart cities. The theme enjoys strong links with the Department of Engineering Science, including a jointly offered CDT in *Autonomous Intelligent Machines and Systems* (awarded to Trigoni as PI).

Data and Knowledge (Head: Horrocks; 8 faculty). This theme, formerly Information Systems, encompasses research in databases and knowledge representation, including query languages, information exchange, data wrangling, factorised and probabilistic databases, in-database machine learning, ontology languages, and reasoning systems.

Foundations, Structures, and Quantum (Heads: Abramsky, Coecke; 4 faculty). The theme encompasses interdisciplinary research into conceptual and structural foundations across a

range of disciplines, including computer science, physics, pure mathematics, and linguistics. It has been strengthened with the hiring of Kissinger (ECR).

Human-Centred Computing (Head: Shadbolt; 5 faculty). The theme was founded following the appointment of Shadbolt in 2014 and Berners-Lee (part-time) in 2016 to join Jirotko; and has been expanded with the hiring of Binns and Van Kleek (ECRs). Research encompasses responsible research and innovation, fairness, transparency, and accountability in data-driven algorithmic systems, and empowering individuals to take better control of privacy and personal data.

Programming Languages (Head: Ong; 5 faculty). The theme has evolved significantly, with the addition of Ong (from Foundations, Structures, and Quantum) and new hires Staton and Murawski (ECR). The theme continues to pioneer the development of algorithmic and algebraic approaches to programming-language semantics, program transformation, and program analysis, with a particular focus on higher-order, probabilistic, and quantum programming.

Security (Head: Martinovic; 9 faculty). This theme has been strengthened with the permanent appointment of Rasmussen. Research encompasses cybersecurity, protocol analysis, wireless security, systems security, trusted computing, human-centred security, and steganography. The theme hosts the interdisciplinary *Global Cyber Security Capacity Centre*, in conjunction with the Oxford Martin School and several other Oxford departments, and a CDT in *Cyber Security*. It also provides the nexus for the *Oxford EPSRC–NCSC Academic Centre of Excellence in Cyber Security Research* (from 2012, renewed 2017–22), a vehicle for collaboration across the University.

This UoA additionally includes Krafft and Wright from the Oxford Internet Institute, with research interests respectively in beliefs and ideology in the information society, and privacy and censorship on the web. Wright is co-director of the *Cyber Security CDT*.

1.3. Research Strategy

Our core objective is to sustain world-leading research across a broad spectrum of computer science, running from foundational work to applied and interdisciplinary research that directly addresses societal challenges. Strategy is formulated in consultation with faculty members during our termly faculty meetings and annual strategic planning away day. Based on this consultation, the Department produces a five-year plan that is reviewed by the MPLS (Mathematical, Physical, and Life Sciences) Division of the University for incorporation into its own strategic plan. Implementation and oversight of research strategy is achieved through the Department's senior management team (including the Head of Department, Deputy Heads of Department for Research and for Teaching, directors of taught programmes, Director of Environment – a new post created in 2019 – and the senior administrative officer), in combination with the Research Committee, whose membership includes, *ex officio*, the heads of each research theme, along with key support staff. Through this process, we have identified five key objectives over the next five years. Here we outline these objectives in relation to progress achieved against the strategic goals we described in REF2014.

(I) Broadening and renewing our research themes. Our thematic structure is a key mechanism for managing our research portfolio and ensuring sustainability. While staff freely pursue their own research agendas, themes provide the critical mass and leadership that is required to attract high-quality staff and students, maintain significant networks of collaborators, lead national and international research initiatives, and secure long-term funding at scale. Plans

for developing themes are guided by our long-term objective of building capacity around cross-cutting challenge areas. These include algorithms in the large; autonomous and intelligent systems; computational healthcare and medicine; dependable and secure computing; data integration and knowledge representation; and human-centred computing. In particular, the establishment of new themes in Artificial Intelligence & Machine Learning (AI&ML), Cyber-Physical Systems (CPS), and Human-Centred Computing (HCC) has expanded capacity around autonomous systems, big data, and machine learning – areas we highlighted in REF2014 as having strong potential for impact generation. Planned growth over the next five years focusses on these new themes. We aim to expand AI&ML and HCC with further appointments, and to grow and broaden CPS with hires in the general area of Systems (for example, distributed systems, networks, etc.). In AI&ML, we will appoint a new chair endowed by a substantial donation from Google DeepMind. We will use replacement hires to maintain and refresh those themes that are not marked for expansion.

(II) Ensuring the quality and diversity of research income. To enable highly collaborative and path-breaking work, our research facilitation strategy targets long-term, large-scale grants and research contracts. Over the period, our staff have been PI on four CDTs, two programme grants, and 21 major fellowships (mainly ERC, EPSRC, and Royal Society), as well as several substantial (>£500k) industrial research contracts. Over the coming period the Department's Research Committee will coordinate programme grant applications in response to a new institutional initiative to pump-prime such applications with internal funds.

In REF2014, broadening our funding base to ensure a sustainable funding stream was identified as the single most important component of research strategy. Section 3 demonstrates strong progress made against this goal since 2014.

(III) Exploiting new opportunities for interdisciplinary collaboration. Over the coming period, we aim to capitalise on opportunities for interdisciplinary collaboration in AI and machine learning. Within Oxford, The Big Data Institute, Engineering Science, Mathematics, and Statistics all have significant activity in machine learning. Shadbolt, who leads our HCC theme, is Chair of the Steering Committee for the new *Oxford Centre for Ethics in AI*, a principal beneficiary of a record-breaking £150m donation for a new centre for the humanities that will generate significant opportunities for cross-disciplinary work. We aim to use new appointments to build collaboration here. Another major focus will be the University's plans for a new building for Oxford's Information Sciences, co-locating CS alongside relevant faculty from Engineering Science. This will provide high quality, purpose-designed space, strengthen existing interdisciplinary links (for example between our CPS and AI&ML themes and the vision and robotics groups in Engineering), and create opportunities to develop new areas of collaboration. Further exciting opportunities for interdisciplinary work will arise from the creation of Reuben College, a new graduate college of the University that has AI&ML as one of its three primary research themes and will admit its first cohort of graduate students in Autumn 2021. These opportunities at the institutional level complement our strategy of supporting interdisciplinary collaboration nationally and internationally through participation in programme grants and large-scale initiatives.

(IV) Expanding recruitment and funding of research students. Through both RAE2008 and REF2014, increasing the number of doctoral students has been a core strategic objective. We currently graduate an average of 34 students per annum: a 39% increase over the REF2014 period. Key future objectives are (i) to secure more funding for doctoral training from research councils, industry, and through fundraising in partnership with colleges; (ii) to further improve the

pipeline of excellent students through outreach, by updating our MSc and arrangements for research internships, and through formal international collaborations. An example of the latter is a forthcoming joint doctoral programme between the Department and the Max Planck Institute for Software Systems, due to start in 2021.

(V) Developing strategic collaboration. An overarching priority for the coming period will be to develop long-term partnerships that contribute to scientific quality, impact, and research income. This goal builds on existing collaborations at national and international levels, including our ongoing leadership role within the Alan Turing Institute, new strategic industrial collaborations (see Sections 1.4, 3.1, and 4.1), and new formal collaboration agreements with universities in Hong Kong and Japan, encompassing exchange research visits, joint participation in grant applications, and joint PhD supervision (Section 4.1). New collaborations will be assessed in terms of risk and potential contributions to other strategic priorities.

1.4. Impact Strategy

The impact strategy presented in REF2014 has led to a transformation in the significance and reach of the impact arising from our research. Below we review this strategy and describe how it is being updated over the next five years.

(I) Developing impactful research themes. Following through one of the two overarching principles of the impact strategy we identified in REF2014, we have *(i)* expanded research capability in areas with strong potential for impact (see above), and *(ii)* ensured that we can exploit the resulting opportunities by establishing effective structures for realising impact.

i) For example, in REF2014, we identified particular opportunities in autonomous systems. Here, patented indoor positioning technology developed by the new CPS theme has been deployed by the spinout company Navenio to improve the productivity of hospital support services (Impact Case Study [5]). Simulation of human behaviour using deep reinforcement learning, developed by the new AI&ML theme, is being used by Waymo in its development of self-driving cars. Interdisciplinary research of our new HCC theme, meanwhile, has had substantial impacts on public policy (Section 4.1).

ii) Key means of supporting impact realisation have been our flexible policies on reduced FTE (see below), and our engagement with Oxford Sciences Innovation (OSI), an independent investment fund founded to commercialise the University's science and engineering research. OSI has raised £14.6m over the period to support spinouts from CS. These activities have had a transformative effect on our Automated Verification, Data and Knowledge, and Programming Languages themes, allowing them to apply their tool-building expertise to commercial software engineering and data management. Tools supporting test generation and variant analysis for large codebases have been marketed by the spinout companies DiffBlue and Semmlle (Impact Case Study [4]). Three spinouts – Wrapidity, DeepReason.ai, and Oxford Semantic Technologies – have been built around tools that automatically extract and convert raw data from the web and other diverse sources into structured, machine-readable knowledge (Impact Case Studies [1] and [2]).

(II) Impact through interdisciplinarity. This was the second key principle of our REF2014 impact strategy. We support interdisciplinary research by developing and maintaining research themes – such as Security, Computational Biology and Health Informatics, and Human-Centred Computing – which are explicitly interdisciplinary in outlook. As described in Section 4.1, this strategy has allowed us to expand the reach of our impacts over the period to encompass: the developing world (through the work of the *Global Cyber Security Capacity Centre*, led by the

Security theme in collaboration with the Blavatnik School of Government, Oxford Internet Institute, Saïd Business School, and Department of Sociology); regulatory thinking and industry practice in the biomedical sector (through interdisciplinary work by our Computational Biology theme); and public policy in the UK and EU (through interdisciplinary work in our HCC theme).

(III) Engaging with beneficiaries. Fulfilling plans announced in REF2014, we employ a full-time industrial liaison administrator responsible for managing relationships with industrial partners (e.g., consultancy, research funding, student sponsorship, secondments, Department open days). Engagement also happens at the thematic level; for example, in 2017 the Computational Biology theme organised a two-day symposium in Oxford on “In Silico Drug Safety and Efficacy”, which brought together over 100 participants from academia, industry, and regulatory agencies. We also participate in institutional-level outreach, such as the 2019 AI@Oxford conference, a two-day event that included over 500 delegates from the University and from industry, in which our AI&ML, CPS, and HCC themes were extensively involved.

As described in Sections 3 and 4, a wide variety of companies, charities, and government agencies participate in our research projects, both as partners in competitively-awarded grants and through direct funding. At the census date, the value of active directly-contracted research projects was over £4.5m. We also host long-term visits from industry; for example, Ziyad Hanna, Vice-President of R&D at Cadence Design Systems, was awarded a three-year Visiting Professorship that led, among other things, to collaboration on Kroening’s and Melham’s *CREST* Impact Acceleration Project.

Developing relationships with industry, government, and the third sector will be a central strategic aim over the next five years. We plan to expand our liaison activities, and foresee new opportunities arising from the activity of our spinout companies, such as the formal collaboration with Samsung that emerged out of Samsung’s investment in Oxford Semantic Technologies. A further key instrument has been our flexible policy for staff leave and secondments. Over the period, Blunsom, Kroening, Lane, Trigoni, and Whiteson all had temporary reductions in FTE, either to develop spinouts or for secondments to industry. We have recently consulted on and updated our policies on reduced FTE in order to better support individuals to balance their departmental responsibilities with external commitments.

(IV) Incentivising and supporting impact generation. Impact generation is a contributory factor in departmental hiring and promotion decisions. We support impact realisation through the provision of training and internal funding, and by incentivising and rewarding staff. We promote courses run by the MPLS Division on topics such as protecting intellectual property and scientific entrepreneurship; these have been well used by both staff and doctoral students (over 90 participants from CS recorded over the period). The University manages competitively-awarded internal funding sources, such as EPSRC Impact Acceleration Account (IAA) funds, to support engagement between researchers and end-users and to develop new technologies to the point that they are ready for commercial exploitation. Our Research Support team has facilitated broad participation by CS staff in these schemes: since 2014, over 30 projects have received IAA awards, worth over £1.5m in total, with PIs from nine of our ten research themes. Several have led directly to impacts beyond academia, such as the commercialisation of Rogers’s work on acoustic devices for conservation professionals, facilitated by an IAA Technology Award for 2017–20. The Department has created a similar local fund, with two calls during the period allocating around £200k in impact seed grants. One award was instrumental in the development of Impact Case Study [3]. Since 2014, six CS staff have been recognised by Impact Awards as part of a scheme run by MPLS, evidencing the success of these initiatives. We will continue to

pursue this strategy in the coming period, with new calls for IAA and further rounds of departmental impact funding.

Relationship with case studies. Four of our Impact Case Studies involve spinout companies. These have all benefitted from our flexible reduced FTE policy, allowing the founding academics to provide initial leadership and management. Three of the companies received investment capital from OSI. Martinovic's work on aviation security was supported by £30k of Departmental funding for impact realisation. Our strategic focus on obtaining large grants has been instrumental in enabling the transformative research that underpins the case studies. The spinout Wrapidity is based on technology to automate data extraction originally developed in Gottlob's ERC *DIADEM* grant. The DeepReason.ai spinout is based on the Vadalog system developed in research funded by Gottlob's *VADA* EPSRC programme grant. The Oxford Semantic Technologies spinout exploits the RDFox technology developed by Cuenca Grau, Horrocks, and Motik in research funded by Horrocks's *DBOnto* EPSRC platform grant, and Motik's *MaSI3* and *AnaLOG* EPSRC fellowships. Rasmussen's work on Bluetooth arises from his Royal Society fellowship.

1.5. Research Culture

Responsible research. We aim to lead within the University and nationally in developing new standards in research ethics in ICT, particularly through the work of our HCC theme. In 2018, the Department established its own local Ethics Committee, with significant input from the HCC theme and under the guidance of the central University research ethics team. The aims were to raise the profile of research ethics, particularly in response to the emergence of new ethical challenges (for example, connected with AI and algorithmic fairness), and to improve the quality of the ethics clearance process. By 2019, the scheme had already seen more than 60 applications. Beyond the University, the Department plays a leading role within the EPSRC's strategy for promoting ethical research in ICT, through Jirotko's *Observatory for Responsible Research and Innovation* (ORBIT) centre, launched in 2018 (see Section 4). Shadbolt and Berners-Lee are co-founders and Board members of the *Open Data Institute*, a non-profit working with companies and governments to build an open, trustworthy data ecosystem that supports better data-driven decision making. With around 60 employees, the Institute has established a world-leading position in open data research and technology, making significant contributions to UK and other governments' open data policies. Rodriguez is a Board member of the National Centre for the Replacement, Refinement and Reduction of Animals in Research (NC3Rs); her group's work on *in silico* modelling has twice been recognised by the NC3R's top international prize for its potential to reduce *in vivo* testing.

Open research. In addition to the culture of open research and open data within the discipline – for example, from 2014–20 our staff uploaded over 1,400 research papers to the open distribution service arXiv – the Department actively promotes Oxford's open access policies, which aim to ensure the widest possible access to its research. There is an academic advocate for Open Access (Živný), and two CS librarians act as Open Access contacts. Gavaghan is on the Steering Group for *Reproducible Research Oxford*, the local node of the UK Reproducibility Network, which promotes a coordinated approach to open scholarship and research reproducibility across disciplines. The Department has implemented several initiatives to promote the University's commitment to "Green" Open Access via its open repository, the Oxford Research Archive (ORA). We deploy bespoke software that crawls internet databases and issues monthly reminders to researchers to "act on acceptance" by immediately depositing accepted publications in ORA. A research administrator monitors deposits.

2. People

The aims of our people strategy are to recruit personnel with either a record of or the clear potential for outstanding, agenda-setting, and transformational research and innovation; and to support and incentivise their career development. As described below, we do this through mechanisms for mentoring, training, appraisal, promotion, financial support, and teaching relief.

2.1. Staff

Our return includes 69 academic faculty from Oxford CS and ten research staff (four from Oxford CS, two from Oxford Internet Institute, and four from Oxford's constituent colleges). Figure 1 illustrates growth in the Department since REF2014. The 69 faculty comprise 38 Professors, 23 Associate Processors (APs), and eight Departmental Lecturers (DLs). Five DLs are on fixed-term positions funded by salary buyouts accruing from research fellowships. The role gives ECRs an ideal opportunity to engage with the full range of academic duties (including research), comparable to a starting AP, and is an important vehicle for career development.

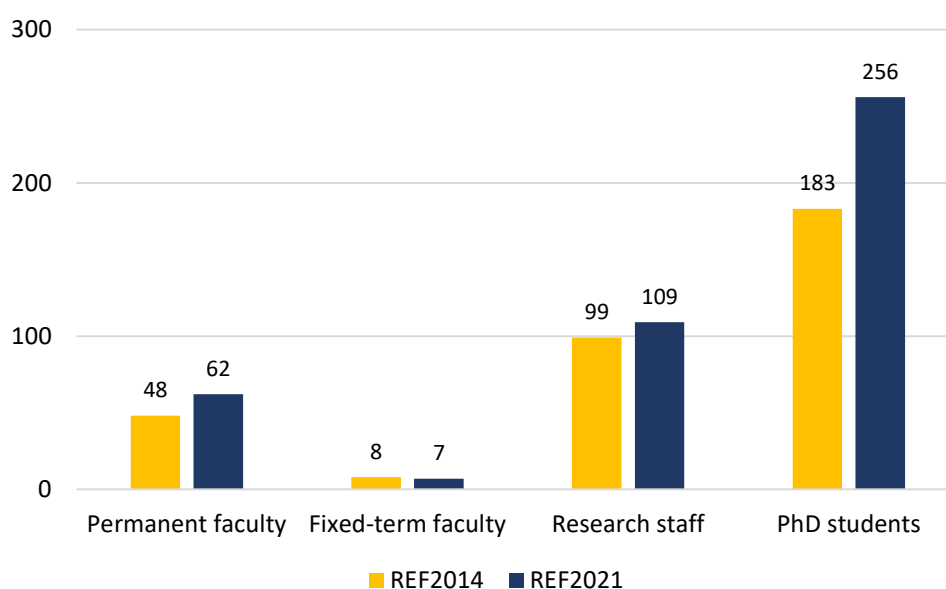


Figure 1: Departmental headcounts REF2014 vs REF2021

Recruitment. The expansion in our research capability has been underpinned by 13 new hires across our research portfolio at AP level, and three hires at Professor level. Our recruitment strategy prioritises research quality and impact creation, within the context of our strategic plans for developing the Department's research portfolio and the need to maintain a balanced profile of experience within themes. Seven of our 13 new hires at AP level are ECRs; overall, 62% of staff returned here are under 50, and 23% are under 40. Only three of our research themes have an average age over 50, and none of these over 51. We recruit from an international talent pool: more than half of our staff come from outside the UK. In order to identify the best possible candidates, we use search panels to identify and approach potential applicants. We will continue to pursue a range of avenues to further broaden the field of applicants, including hiring in batches, open hires across our research themes, and synchronising with the international recruitment cycle.

Mentoring and career development. As evidenced in Section 3, we have a strong record of supporting staff, particularly early career staff, to build up their funded research programmes and academic careers. New staff receive start-up funding for travel, students, and equipment, with

junior staff having a reduced teaching and administrative load. All new staff receive a training plan that includes courses in doctoral supervision, being a PI, equality and diversity, and unconscious bias. Newly appointed APs have a five-year probationary period and receive formative advice and guidance as part of a formal review after three years in post. There is a further review after five years, when a decision is made on reappointment to retirement based on a rigorous assessment of research, teaching, and citizenship, supported by external references. All academic staff are assigned a mentor to provide support, guidance, and advice relative to their level of experience. Staff also complete an annual workload survey, which is used as a basis for balancing the assignment of teaching, management, and administration duties. Staff can request feedback or an appraisal. We aim to retain talent, but our effectiveness in supporting staff to develop their research profiles means that when faculty do leave it is generally to take up prestigious senior positions in academia or in industry. Olteanu, for example, joined as an early-career researcher in 2005, was promoted to Professor in 2016, and left in 2020 to head the Data Systems and Theory Group at Zurich; De Freitas left in 2017 to become a lead scientist at DeepMind following DeepMind's acquisition of his spinout company Dark Blue Labs.

Reward and recognition. We hold annual promotion rounds, based on merit and without quotas. Staff in Grades 9-10 – typically senior researchers and Departmental Lecturers – are eligible to apply for the title Associate Professor through an annual scheme. Since 2014, there have been ten successful applications. If already in an AP or other eligible role, staff can apply for Professor title through an annual Recognition of Distinction scheme. Since 2014, there have been twelve successful promotions from AP to Professor (including four women). The post of Departmental Lecturer has three grades and several of our permanent DL team have been regraded after assuming greater responsibilities. The Department encourages PIs to consider regrading ECRs who demonstrate independent research and take up greater responsibilities. Since 2014, eight fixed-term researchers have been promoted from Grade 7 (junior researcher) to Grade 8 (senior researcher). The University runs an annual merit-based award scheme that gives a salary uplift to employees with the Professor title, based on an assessment of their contributions in research, leadership, and teaching. Impact generation is taken into account as a contributory factor in Departmental hiring and promotion decisions. It is also recognised by Impact (and associated pay) Awards from a scheme run by MPLS: six CS staff have won Impact Awards in the period.

Supporting research. The Department is committed to protecting the time available for research as well as supporting applications for fellowships and sabbatical leave. All academic staff are entitled to one term of sabbatical leave for every six terms worked. Staff are fully funded during sabbatical leave.

Supporting engagement and impact. Academic and research staff have a contractual entitlement of up to 30 days per annum when they can be paid for outside work. This is usually personal consultancy but can include other work: examples in this period include an extended sabbatical to work with the House of Lords (see Section 4.1 for evidence of engagement with policymakers) and reduction of duties to sit on national REF panels. Over the period, 54 CS staff have undertaken 122 personal consultancy agreements through Oxford University Innovation (OUI), the University's technology transfer office. Doctoral students are also encouraged to undertake commercial internships, with the senior administrator providing contractual support for this process to ensure that students can achieve commercial experience alongside their studies.

Section 1.4, above, contains further evidence of how we enable engagement with beneficiaries, including our flexible policy for reduced FTE.

Early career researchers. The Department has fully implemented the revised Concordat on ECRs. The role of ECR Coordinator was constituted in 2019 to work with the Director of Environment to support ECR development, integration, and networking. The ECR Coordinator has organised a series of training and social events, such as seminars in partnership with our Research Support team on applying for grant funding. Compulsory annual Career Development Reviews were implemented in 2016 to provide a structured opportunity for PIs and ECRs to reflect and plan for career development in the current role and beyond, and to discuss opportunities that would enable staff to meet their career aspirations. This scheme has been very successful. From 2018, research staff have been supported to take a minimum of ten days per annum for professional development and training. ECRs are encouraged to attend MPLS training, identified through their Career Development Reviews, in subjects such as entrepreneurship, good practice in research, thinking about impact, being a PI, public engagement, and applying for funding. Over the period, ECRs have attended over 120 such courses. Within the Department, ECRs are encouraged to organise seminar series. The Department and colleges also provide extensive opportunities for teaching assistantships and ad hoc lecturing, thereby providing essential experience for a future academic career.

A measure of our effectiveness in nurturing academic careers is provided by the list of institutions at which PhD students and Research Assistants within the Department over the period have subsequently obtained permanent faculty positions. These include Birmingham, Bristol, Cambridge, Edinburgh, Imperial College, Kent, Liverpool, Newcastle, Manchester, Oxford, Royal Holloway, Southampton, UCL, York, and, overseas, at Australian National University, Cape Town, CNRS (France), Dresden, Monash, National University of Singapore, Technion, Toronto, TU Delft, U Illinois, U Colorado, ULB Brussels, Warsaw, and Vienna.

2.2. Doctoral Students

Recruitment. The Department receives around 400 applications annually for its doctoral programme; around 50 students are recruited. To promote our programmes, we hold graduate open days, with dedicated taster days for CDTs. The baseline expectation for admission is a first-class degree in a 4-year programme in computer science or a cognate discipline. Suitably qualified applicants are interviewed by at least two academics and considered for funding by the Scholarship Committee. We track the number of female applicants and these data have been used to make a case for targeted scholarships in our fundraising (see below).

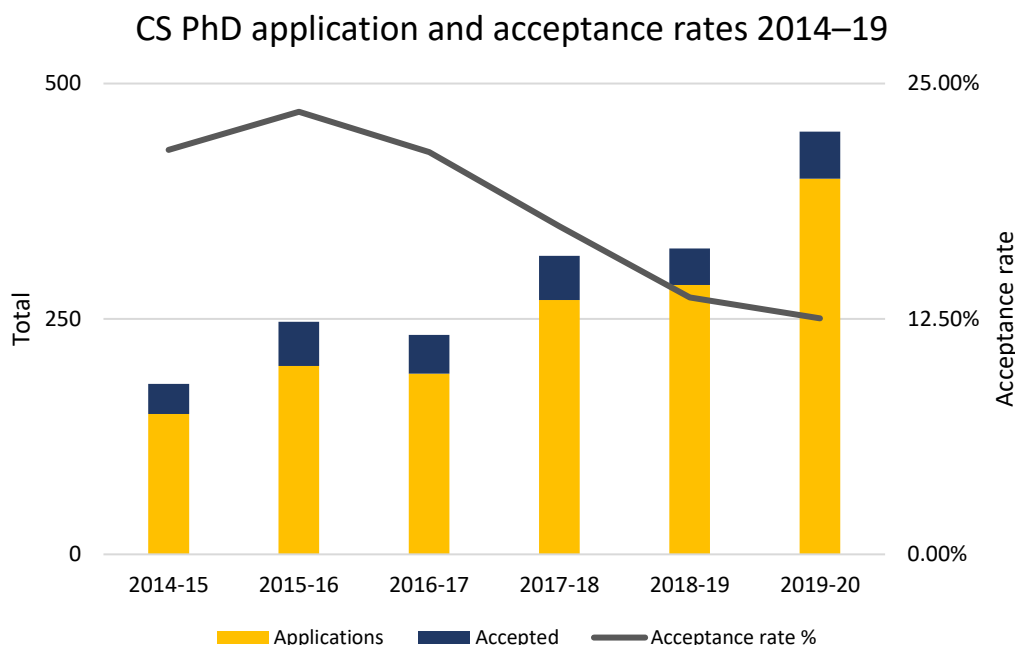


Figure 2:

Average annual growth in applications since 2014-15 is 22% overall, and 25% for female candidates. Entry is highly competitive.

Funding. The large increase in doctoral students over the period has been underpinned by our participation in, and leadership of, centres for doctoral training (CDTs), in partnership with Engineering Science, the life sciences, and Oxford's Big Data Institute. Over the period, doctoral students in CS have received funding from six EPSRC centres for doctoral training (CDTs), of which four are or have been led by PIs from CS. The Department participated in two CDTs awarded in 2012 and 2013 EPSRC funding rounds: *Cyber Security* (2012) and *Autonomous Intelligent Machines and Systems* (2013). The former, led by A. Martin in the Security theme, was awarded second-phase funding of £3.5m in 2016. Our staff were PI for three CDTs awarded in the EPSRC's 2018 round: *Health Data Science* (Davies, £6.6m), *SABS:R³* (Gavaghan, £5.3m), and *Autonomous Intelligent Machines and Systems* (awarded to Trigoni, £5.2m). Students have also received funding through the EPSRC CDTs *Life Sciences Interface* and *Systems Biology*. Other collaborative doctoral training programmes in which we participate include the BBSRC Doctoral Training Partnership, the Wellcome Trust *OXION* programme, and the BHF Cardiovascular Sciences programme. Further substantial funding for doctoral students comes from scholarships administered by the Department and central University. A donation of £2.7m from DeepMind in 2014 was used to support scholarships, including two doctoral studentships endowed in perpetuity. Overall, 75% of doctoral students are fully funded, with EPSRC funds accounting for just under half the total number of studentships. The Department gives all doctoral students a baseline travel budget of £2k. This is complemented by further travel funding from colleges (up to £1.5k over the course of the degree).

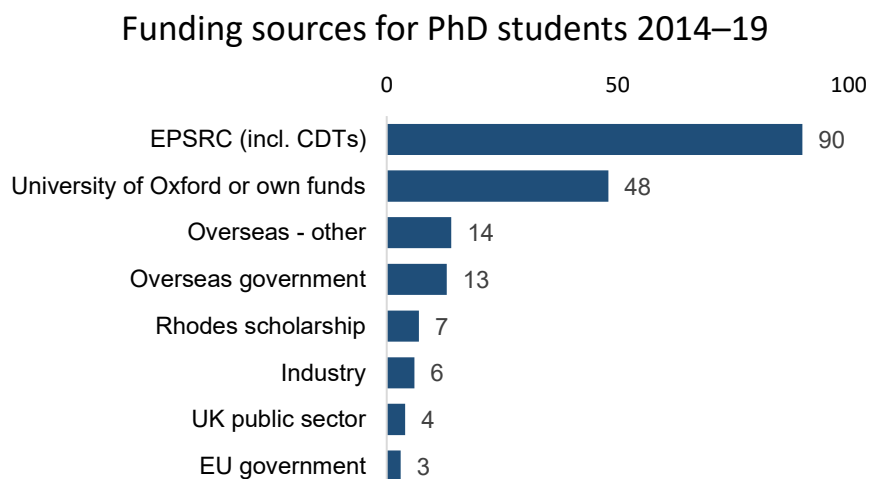


Figure 3: Funding for doctoral students is drawn from various sources, with a majority supported by research council funding and competitively-awarded scholarships.

Monitoring and appraisal. Every doctoral student is a member of a college, with a personal advisor and access to welfare support and hardship funds. Within the Department, each student has at least one primary supervisor, as well as a secondary advisor who can provide extra support. Pastoral care for graduate students is overseen by the Director of Graduate Studies and the Graduate Studies Administrator. There is a termly supervision framework, involving submission of progress reports from both student and supervisor(s). The reports are evaluated by the Director of Graduate Studies and college advisors. They allow students and supervisors to monitor progress and review training needs. Doctoral students are initially admitted under probationary status and are required, after the first year, to pass a *transfer examination* involving the submission of assessed work, a qualifying dissertation, an oral exam, and a record of transferable skills training, all considered by two examiners. In the third year, and before being allowed to submit a thesis, students undertake a second formal evaluation involving both a viva and written component. The effectiveness of the structures for monitoring progression is reflected in low attrition rates: of doctoral students due to submit within the assessment period, 7.5% have withdrawn, while the remaining 92.5% have successfully passed the degree.

Skills, training, mentoring, and career development. In partnership with the MPLS Division, we provide training and advice for all doctoral students in research practices, transferable skills, and career development, including academic writing, grant applications, presentations, entrepreneurship, and completing a doctorate. In particular, through MPLS's Graduate Academic Programme, our doctoral students have access to over 300 courses run by departments within MPLS and have altogether attended over 800 such courses since 2014. CDT students additionally have their own dedicated skills training programmes. The Department's *Oxford Computer Science Conference* and the annual *Oxbridge Women in Computer Science Conference* also provide opportunities for students and researchers to develop presentation skills and receive feedback from peers. Female graduate students are encouraged to enrol on the Springboard course, which enables students to discuss career paths with female peers and researchers. The Department hosts a weekly lunchtime "tech talk" seminar series for doctoral students, providing a forum for companies to talk about both product development and career opportunities. Recent participants include Omnittek, Apple, Morgan Stanley, and Netcraft. As well as successful careers in academia (Section 2.1, above), PhD students in the period have

progressed to a range of high-profile careers in industry: examples include at Google Research, Zurich; DeepMind; Drive.ai; Facebook; and Bloomberg.

2.3. Equality, Diversity, and Inclusion (EDI)

Departmental structures and working practices. We aim to integrate equality and diversity throughout our recruitment and staffing policies, and to prioritise inclusivity and wellbeing across our working practices. We believe this is the best way to pursue our mission of academic excellence and to enable all our staff and students to achieve their full potential.

Our Equality and Diversity Committee meets termly, and includes the Head of Department, ECR Coordinator, senior administrative staff, and, since 2019, the Director of Environment – a post created specifically to champion EDI. We are a Stonewall employer, and benefit from diverse representation in highly visible leadership roles: for example, female professors lead four of our ten research themes; Trigoni, who leads the CPS theme and founded the spinout Navenio in 2015, won CTO-of-the-year at the 2020 Women in IT awards. We successfully retained our Bronze Athena SWAN award in 2018. The Director of Environment spearheads implementation of our current Athena SWAN action plan: initiatives already implemented include outreach activities and studentships to encourage applications from females to our doctoral programme.

As described above, we seek to recruit from the widest possible international talent pool and use search panels to help ensure that we can identify the best possible candidates, including among under-represented groups. We offer support towards the cost of caring commitments to those invited for interview for a faculty position. Since 2017, PIs have been encouraged to advertise research positions on both a full-time or part-time/job share basis, where possible, in order to reduce barriers for potential applicants.

The University has a well-established flexible working policy, which allows for various options including part-time working, working from home, job-sharing, and compressed hours. During the period, six CS staff have moved formally to flexible working arrangements. We encourage returning staff to apply to the University's Returning Carers Fund, a small grants scheme to support the return to research of individuals who have taken a break for maternity or other caring responsibilities. One applicant was awarded nearly £5k, enabling her to attend relevant workshops and conferences on return to work.

The Department prioritises wellbeing and maintains a team of approximately 15 Mental Health First Aiders, drawn from all categories of staff and students, which meets termly to organise event programmes focussed on mental health and wellbeing. We also use an Employee Assistance Programme (Validium) to provide advice and counselling to staff and students.

Funding and access. EDI is a standing item at the Department's Research Committee, and the committee scrutinises the diversity profile of staff being supported in funding applications. CS staff are currently participating in a project, *Improving Researcher Diversity in Research Funding Success*, which aims to identify systemic barriers for BAME, LGBT+, and disabled researchers, and to work with key funders to improve the funding system and create targeted support. The project is supported by £25k from the University's central Diversity Fund. We have sought to engage industrial sponsors to offer financial support for students from traditionally under-represented groups. In 2018-19, the Department awarded two fully-funded doctoral scholarships for female students, funded by DeepMind. We have also provided support for students on our MSc degree, which has a significant research component and is an important pathway to doctoral study. Booking.com gave six MSc studentships in 2018-19 for women studying for an

MSc in CS. DeepMind funded four MSc studentships in 2019-20 and again in 2020-21 for females, BAME students, or students from households with traditionally low progression to higher education. The Department also participates in the University's UNIQ+ graduate access internship programme. This programme, which provides a six-week supervised research project, is aimed at talented undergraduates at UK universities who would find progression to graduate study a challenge for non-academic reasons.

Promoting diversity. The Department has supported numerous initiatives that have helped to raise the profile of EDI issues and to encourage greater diversity within the discipline. In 2019, Jirotko's ORBIT centre organised and hosted the first "100+ Brilliant Women in AI & Ethics" conference, supported by the Alan Turing Institute, Microsoft, and PWC alongside the Department. Within CS, the *Oxford Women in Computer Science Society (OxWoCS)* was founded in 2013 to support and promote women in computer science, including faculty, staff, and students. We provide OxWoCS with £4k in annual direct support for seminar speakers and travel funding to the annual Grace Hopper Celebration, the world's largest gathering of women in technology. We also provide indirect support, such as mentoring and administrative assistance. OxWoCS won the inaugural Equality and Diversity Award from the MPLS Division, and has received industrial sponsorship from Google, Bloomberg, Facebook, J.P. Morgan, GSK, and VISA. Among the sponsored events is an annual conference, *Oxbridge Women in Computer Science*. The sixth iteration was held in 2019, with over 70 participants (over 90% of whom were female) and featuring Dame Stephanie Shirley as invited speaker. OxWoCS also hosts a Distinguished Speaker Seminar for female academic and industry leaders. Selected speakers over the period include Shafi Goldwasser (MIT, Turing Award winner), Claire Vishik (Intel, FRS), Xin Luna Dong (Amazon, ACM Distinguished Member), Tova Milo (ACM Fellow), and Natasha Noy (Stanford, Google).

EDI and REF. Many actions were taken at the level of the UoA to ensure the operation of a fair and transparent process in the construction of the unit-level REF submission. These included REF-directed unconscious bias training for staff with decision-making roles, and the formation of an advisory REF committee with broad representation from across the UoA in terms of career stage, gender, and disciplinary focus. To ensure rigorous, transparent, and fair selection of outputs, we first scored and ranked outputs based only on reviews and panel moderation. We then analysed the results against diversity criteria to check for systematic bias. Although for most known groups the numbers were too small to be statistically significant, our analysis showed that the average number of outputs attributed to female staff was greater than the overall average. ECRs (who comprise 20% of staff returned here) are also well represented in our output selection.

3. Income, infrastructure, and facilities

3.1. Research Income

We report total external research income (expenditure) of over £74m for the assessment period. This continues a steady upward trend in both total average annual income and average annual income per FTE, evidencing progress made in consolidating the broad and sustainable research base built up since RAE2008. Over the current period, we have continued to pursue our aims to diversify our funding portfolio and to secure large, long-term grants that allow our staff to focus on fundamental and agenda-setting research, and to collaborate with a wide range of partners in academia, industry, charities, and the public sector. As Figure 4 shows, we have drawn income from a diverse mix of sources, with UKRI funding representing less than half of total income – 39%, down from 55% over the previous period. Funding from charities has grown significantly (a

sevenfold increase in terms of value, from around £650k in REF2014 to over £4.5m), while funding from industry has doubled in value to over £6m. As detailed below, we have also achieved increased success in winning large, longer-term grants during the current period (24 grants of five years' duration or longer, 20 at £1m+), with PIs from the Department leading two EPSRC programme grants. This success reflects both our investment in research support capacity and a culture in which staff are encouraged and supported to develop ambitious research goals that will underpin their long-term career development. At the census date, 49 staff in the UoA (out of 79 returned here) held grants – including 41 as PI – with a total value over £36m, and an average value per grant of c. £370k. Our staff have already secured future grant income worth over £21.5m up to 2025.

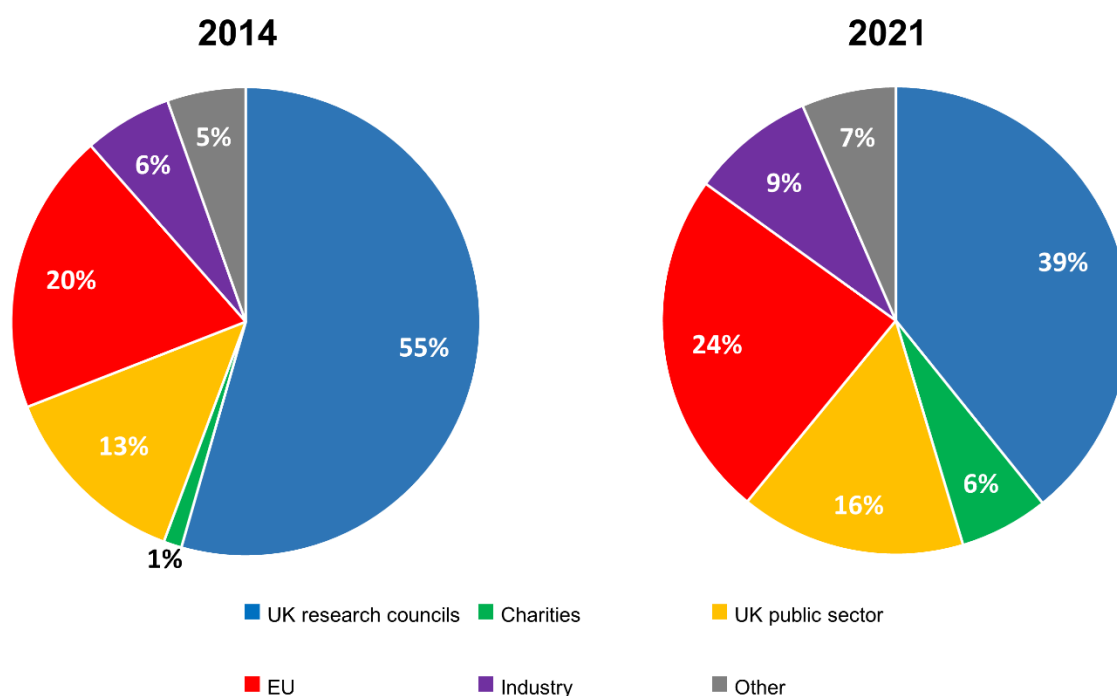


Figure 4: Sources of research income: REF2014 vs REF2021

Large grants and fellowships. Across all its research themes, the Department has been successful at winning long-term, large-scale funding, including programme grants and fellowships. Our staff have established strong strategic partnerships with industry and public sector stakeholders, and numerous emerging collaborations will help to ensure the future sustainability of this wider engagement. Our success in these areas reflects and underwrites our strategic goals to foster national and international collaboration, expand our support for doctoral training, and nurture our staff in developing their careers and assuming leadership roles in their fields.

Large collaborative grants led by our staff include:

- Shadbolt's £6.2m *SOCIAM* EPSRC programme grant (£1.2m for Oxford), with Southampton, Edinburgh, Northwestern, and Tsinghua, and many industry and public sector partners. Along with the EPSRC-funded *PETRAS* (Privacy, Ethics, Trust, Reliability Accessibility and Security) and *PETRAS2* Hubs, in which our HCC theme has collaborated alongside members of our Security theme, *SOCIAM* has supported research into tools and systems designed to improve end-users' ability to conceptualise and control their privacy online. Outcomes include a series of studies relating to privacy in the context of smartphones and smart home devices, including analysis of 1 million

apps, resulting in best paper awards at leading venues such as ACM CHI and ACM WebSci'18, and in engagement with policy-makers (see Section 4.1).

- Gottlob's £4.5m *VADA* EPSRC programme grant (£1.88m for Oxford), with Edinburgh and Manchester, and industry partners including Facebook and Microsoft. Together with Gottlob's *DIADEM* ERC grant, this has led to significant theoretical and practical advances in Datalog-based logical reasoning systems, directly generating two spinout companies within the REF period (Wrapidity and DeepReason.ai).
- Horrocks' *DBOnto* EPSRC platform grant (£1.26m). Along with Motik's *MaS/3* EPSRC fellowship, this has supported work on consequence-based reasoning, the theory and practice of Datalog, and combinations of logic and arithmetic functions. New theoretical and practical insights achieved in this research have led to best-paper awards, publications in top AI venues, and significant real-world impacts through the development of both open source and commercially marketed reasoning systems (Impact Case Study [2]).

In addition:

- Kwiatkowska and Trigoni are Co-Investigators on the £5m EPSRC programme grant *Mobile Robotics*, led by Oxford's Engineering Science department, with partners including Berkeley, McGill, the Department for Transport, UK Atomic Energy Authority, and UK Space Agency.
- Horrocks is Co-Investigator on the £5.1m EPSRC programme grant *UK FIRES* led by Cambridge, with collaborators at Bath, Imperial, Nottingham, and Strathclyde, alongside many industry partners.

Substantial direct support for research includes funding from Amazon Web Services (Jirotko and Trigoni, £2m); DeepMind (endowing a new Chair in AI); AXIS UK Services (Creese, £1m); Samsung UK (Horrocks, £500k); and FCDO (Foreign, Commonwealth and Development Office) (Creese, £350k). FCDO funding supports the work of the Global Cybersecurity Centre as part of a programme to help partner countries develop cybersecurity capacity in line with the UK's Aid Strategy. Funding from Amazon is part of a long-term research collaboration with CS and Engineering Science at Oxford, announced in 2020 and backed by a £7m gift, and is supporting the establishment of an Institute in Responsible Innovation by Jirotko. DeepMind's donation followed their acquisition of our Dark Blue Labs spinout in 2014. Funding from Samsung is part of a new formal collaboration with members of our Data and Knowledge theme, aimed at developing knowledge representation techniques to build user-oriented AI. The relationship builds on the role of Samsung Ventures in raising £3m for the spinout Oxford Semantic Technologies, and bolsters the theme's strong links with industry, which include, for example, a long-standing collaboration with Siemens that has resulted in substantial doctoral studentship funding and contributions to major UKRI-funded projects.

We have a strong track record in supporting staff to apply successfully for competitively-awarded research fellowships. We provide mentoring and guidance to help staff develop proposals, and mock interviews for all shortlisted applicants, with tailored guidance for ECRs (see section 2.1 above). These structures are an important part of our strategy to support staff in developing their research profiles: among ECRs who have obtained prestigious fellowships in this UoA since 2014, Bueno-Orovio, Haase, Heunen, Rasmussen, and Vicary have all gone on to permanent academic jobs. Building on our success in the REF2014 period, CS staff have

been awarded many substantial research fellowships within the current period, including: six ERC Starting grants (Elkind, Haase, Lane, Lin, Whiteson, Živný); two EPSRC Early Career Fellowships (Blunsom, Heunen); three ERC Consolidator grants (Ouaknine, Olteanu, Santhanam); one ERC Advanced grant (Kwiatkowska); five EPSRC Established Career Fellowships (Benedikt, Jirotko, U. Martin, Motik, Worrell); three Royal Society University Research Fellowships (Rasmussen, Staton, Vicary); one Royal Society Research Professorship (Gottlob), in addition to the Royal Society Research Professorship already held by Cardelli; an AXA Chair in Explainable AI for Healthcare (Lukasiewicz); and others including Wellcome Trust and British Heart Foundation fellowships (Rodriguez, Bueno-Orovio).

The success of our staff in winning substantial grant funding and fellowships enables them to pursue ambitious research agendas that give rise to research of world-leading quality, generate significant impacts beyond academia, and stimulate and nurture fruitful collaborations.

By way of illustration, four of the eight members of our Algorithms and Complexity theme have been supported by ERC projects in work that has led to fundamental contributions in algorithmic game theory (Koutsoupias), the complexity of computational problems from statistical physics (Goldberg, together with Galanis), connections between algorithmic analysis and computational lower bounds (Santhanam), and the applicability of classical optimisation techniques such as linear and semidefinite programming to Constraint Satisfaction Problems (Živný). In our Automated Verification theme, large fellowships (ERC, EPSRC, and Royal Society) have supported work by Kiefer, Ouaknine, and Worrell on algorithmic properties of dynamical and stochastic systems that has led to the resolution of longstanding open problems, and ongoing work by Kwiatkowska and Haase on novel techniques for the verification of deep neural nets and decision procedures for arithmetical theories. In the AI&ML theme, ERC and EPSRC fellowships have supported Wooldridge's work on the verification of Nash equilibrium properties of multi-agent systems, Elkind's work on novel algorithms for collective decision-making and group formation, Whiteson's work on novel cooperative multi-agent reinforcement learning algorithms, and Blunsom's work on deep learning techniques for natural language applications. In Data and Knowledge, Benedikt has pushed forward understanding of nested data in work supported by his EPSRC fellowship, including new results on the expressiveness of nested query languages and their connections with functional languages. In the Programming Languages theme, work on probabilistic programming supported by Staton's Royal Society URF has led to best paper awards and invited talks and will be built on in an ERC Consolidator project that aims to develop new languages for statistics and probabilistic programming. Murawski has developed the first fully abstract denotational model of an object-oriented language, in work recently published at JACM. In the Foundations, Structures, and Quantum theme, research supported by the EPSRC-funded *Centre for Quantum Mathematics and Computation* has led to new developments of game semantics by Abramsky, whose contribution in this area was recognised by the joint award of the 2017 Alonzo Church prize (with Ong, Nickau, and others). Recent work on new connections between semantics and structural and descriptive complexity, including a pioneering programme at the Simons Institute in 2016 connecting the communities, has led to a four-year EPSRC standard grant with the University of Cambridge and several partners in the US and Europe.

Substantial grants and fellowships have also played an important role in supporting significant impacts beyond academia and collaborations that continue to drive innovative research. For example, the CPS theme has strong links both with Engineering in Oxford (with numerous large joint grants), and with applied machine learning (e.g., in 2018, Lane was awarded a three-year EPSRC-UKRI Fellowship aiming to apply recent transformational developments in deep learning

with Nokia and Samsung). Fundamental and applied research in the theme focussing on intelligent and autonomous sensor systems has led to outcomes that include best paper prizes at leading conferences, significant further funding (e.g., the £5m *Mobile Robotics* EPSRC programme grant, on which Kwiatkowska and Trigoni are Co-Investigators), and three spinout companies formed within the current period (Joulo, Open Conservation, Navenio). As described below (Section 4.1), members of the Computational Biology theme have been supported by fellowships from the Wellcome Trust, the British Heart Foundation, and the NC3Rs, and participate in several large EU and EPSRC-funded collaborative projects. These have enabled significant collaborations with both European and US regulators (EMA and FDA) and with pharmaceutical companies, with outcomes including the development of ground-breaking *in silico* modelling software that predicts clinical risk with greater accuracy than animal testing, and is already in use within the pharmaceutical industry. Further evidence of the wider impact of our research is contained in our Impact Case Studies and below in Section 4.

Philanthropy and college support. Philanthropic donations make an important contribution to our research environment. Over the period, the Department received more than £17m in donations, including £10m towards the planned new Information Sciences building, funds for the DeepMind chair, and £2.7m for graduate scholarships. We will further benefit from a recently announced £7m gift from Amazon Web Services, to be shared between CS and Engineering Science. A donation of £53k by Oxford Asset Management has supported our flagship Departmental seminar, the termly Strachey Lecture, with speakers since 2014 including five Turing Award winners – Vint Cerf, Shaffi Goldwasser, Barbara Liskov, Adi Shamir, and Leslie Valiant – among many other notable computer scientists, including Demis Hassabis, Stuart Russell, Bjarne Stroustrup, and Eva Tardos.

Investment by Oxford's constituent colleges has provided valuable support for graduate studentships and junior research fellowships (competitively-awarded, fully-funded fellowships for junior researchers, typically of 2–3 years' duration). CS has hosted 11 junior research fellows over the REF period. Two colleges have focused philanthropic activities on raising significant funds for junior research fellows, graduate studentships, and academic posts in Computer Science.

3.2. Research Support

CS research support is structured into pre-award and post-award teams. The former (three FTE positions) provides tailored support across all stages of the application process. The team runs twice-termly seminars on topics such as writing grant proposals, preparing a budget, intellectual property, and academic consultancy; arranges face-to-face meetings between representatives of funders and potential applicants; and provides support for applications, including feedback and guidance on draft applications and mock interviews. Our success in winning fellowships and grants is evidence of the team's effectiveness. The post-award team (five FTE positions) manages the financial and reporting aspects of grants held within CS. We also maintain a team of six full-time research software engineers, who have supported research projects both within CS and in other University departments.

3.3. Buildings and Facilities

Developing estates and facilities has been a central component of Departmental strategy across RAE2008 and REF2014. The main development over the previous period was the acquisition of the Robert Hooke Building close to our main site, which was formally opened in 2014. Over the current period, we have expanded floor space by 10%, and invested substantially (c. £660k) in

refurbishment and improvements. As detailed in Section 1, a current priority concerns plans for a new Information Sciences building that will co-locate CS staff alongside relevant faculty from Engineering Science. We are now defining requirements for the building and engaging with donors, with £10m already received, and a target date of 2025 for beginning construction.

IT Support comprises three different sub-teams totalling ten staff: Service Desk, Infrastructure, and Software Development. In 2015 we commenced a three-year investment programme (>£250k) to ensure that the Department operates a low-latency, high-bandwidth, and resilient data network to support research activities. We maintain over 150 research servers, mostly related to GPU-accelerated computing, with additional support from cloud resources, Oxford University's Advanced Research Computing (ARC) service, and national-level infrastructures such as JADE and ARCHER. We also maintain various specialised equipment: the Security theme uses an aviation lab with realistic cockpit simulator; the CPS theme uses a specialist on-site electronics lab and an associated positioning lab equipped with a state-of-the-art Vicon motion capture for prototype sensor development.

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

4.1. Collaboration

Our research is by its nature highly collaborative. Of around 2,500 Oxford CS research outputs published between January 2014 and July 2020, over 50% have an international co-author and over 10% a co-author with an industrial affiliation.² We collaborate extensively with academic partners in Oxford, the UK, and overseas, and with beneficiaries and end-users spanning industry, charities, government, and social enterprises. Our research contributes to the economy both through industrial collaboration and through commercialisation activities.

Academic collaboration. The Department leads and participates in several national research projects and priorities. Oxford was one of five founding partners of the Alan Turing Institute in 2015, and Oxford CS has many links to the institute. Wooldridge is programme Co-Director for AI. Melham is a non-executive Director and Trustee. Over the period, Abate, Benedikt, Gal, Kanade, Olteanu, Horrocks, Lukasiewicz, and Whiteson (CS), and Wright of the OII, have held Turing Fellowships. Gal was one of the five inaugural Turing AI Acceleration Fellows. The Institute has also funded doctoral students and postdoctoral researchers in the Department.

Members of the Foundations, Structures, and Quantum Theme participated in the EPSRC's £38m *NQIT Hub* (part of the UK National Quantum Technology Programme), led by Oxford and involving 29 globally leading quantum centres and major companies. Abramsky, Barrett, and Jirotko respectively led three out of eleven work packages on the research and development programme of this grant. The Computational Biology theme is involved in numerous significant cross-disciplinary collaborations. Gavaghan's project *A new approach to Science at the Life Sciences Interface* is a £4m cross-disciplinary research landscape grant from the EPSRC that includes, among many others, investigators from the School of Psychology at Nottingham and the school of Genetics, Evolution, and Environment at UCL. Rodriguez and her team participate in the *TransQST* project on adverse drug reaction research, funded with EUR14m by the European Innovative Medicines Initiative, and in the *CompBioMed1&2* project to advance the role of computational modelling and simulation within biomedicine, funded with EUR13m under Horizon 2020. The Security and HCC themes participate in the *PETRAS* National Centre of

² Data source: Scopus.

Excellence for IoT Systems and Cybersecurity, a collaborative project involving 12 partner universities, with £23m total funding.

Our CDT programmes involve collaborations (through joint supervision and joint publications) with a number of other Oxford Departments, including Engineering Science, Statistics, the Oxford Big Data Institute, and the Nuffield Department of Medicine.

International collaboration. Academic partners on other large projects include the Perimeter Institute, University of Vienna, UC Berkeley, McGill, University of Pennsylvania, and the University of Virginia. There are established and ongoing collaborations with international research centres such as the Max Planck Institute, where Ouaknine is Scientific Director, and the Sirius SFI (Centre for Research-based Innovation) at the University of Oslo, where Horrocks is Scientific Coordinator. As well as providing links to a network of industry collaborators in the oil and gas sector, Sirius funds several PhD students and a PDRA at Oxford. Our staff contribute actively to international academic networks, such as the *European Laboratory for Learning and Intelligent Systems* (ELLIS), for which Wooldridge is a Unit Director for Oxford. The assessment period has also seen the emergence of new international collaborations beyond Europe and North America. For example, KAIST (South Korea) and Tsinghua (China) collaborated with the HCC theme on Shadbolt's *SOCIAM* programme grant. The *Global Cyber Security Capacity Centre*, hosted in CS and led by Creese and Goldsmith, has received government funding in Australia (to help establish and build links with a new Oceania Cyber Security Centre), South Africa (to establish a new cybersecurity centre at the University of Cape Town), and Norway. In 2020, the Department signed a memorandum of understanding with the Quantum Information, Foundations, and Technologies Group at Hong Kong University to establish an HKU-Oxford joint lab for Quantum Information and Computation, encompassing exchange research visits, joint participation in grant applications, and joint PhD supervision. A similar MOU to support the exchange of graduate students and staff has been signed between the Departments of Computer Science, Mathematics, and Physics at Oxford and Waseda University in Tokyo.

Collaboration with industry and regulators. The Department has extensive collaborations with major software companies. Our programme grants include as partners BT, Facebook, Google, Huawei, IBM, and Microsoft. As an example of collaboration with the broader manufacturing and infrastructure sectors, the CPS theme collaborates with Nissan, the UK Space Agency, BP, Network Rail, and the UK Atomic Energy Authority through the *Mobile Robotics* programme grant. Trigoni's £1.2m EPSRC project *ACE-OPS* also involves collaboration with emergency services, such as the National Fire Chiefs Council. Our Computational Biology and Health Informatics theme develops the simulation frameworks Chaste and Virtual Assay for modelling cardiac and respiratory physiology, with applications to cancer modelling and drug testing. Chaste has been downloaded by research groups at 1,000 unique locations, including at NASA, GSK, and AstraZeneca; while Virtual Assay is commercially licensed to pharmaceutical companies Amgen, Janssen, UCB, and Servier, and is under evaluation by eight further companies. The theme also works closely with regulatory collaborators, including the FDA and the EMA, and with hospital partners including the John Radcliffe in Oxford and the Heart Hospital in London. In addition to industrial collaboration through research grants and direct industrial funding, our staff have received research awards through industry-led schemes for facilitating engagement with academia, e.g., Google Faculty Research Awards (Lin, Kroening, Olteanu, Whiteson), J.P. Morgan Faculty Awards (Calinescu, Wooldridge, Whiteson), and Amazon (Olteanu).

Collaborations with the third sector. Other collaborators have included charities and social enterprises. Our HCC theme has extensive links with the *Open Data Institute*, a non-profit whose mission is to work with companies and governments to build a trustworthy data ecosystem in order to realise the latent value in open data. Shadbolt and Berners-Lee are co-founders and sit on the Board, while Van Kleek delivers training in AI, visualisations and web technologies at the Institute. The Institute has an annual turnover of around £5m and maintains a network of 28 franchised ODI nodes across 18 countries. Meanwhile, The Mental Health Trust and the think tank *doteveryone* are partners on Jirotko's collaborative £1m EPSRC grant *ReEnTrust: Rebuilding and Enhancing Trust in Algorithms* (along with Co-Investigators from Edinburgh and Nottingham universities, and from Amazon and Samsung).

Economic contribution. Our research has generated significant wider economic impact through spinouts, collaborations, and licence deals. CS spinouts attracted over \$70m in commercial funding over the period, and, at the time of Semmler's purchase by GitHub in September 2019, employed over 225 people. Diffblue, a company founded by Kroening and Schrammel to automate the creation of software unit tests, raised \$22m in Series A funding in 2017, and has deployed its technology at Goldman Sachs and other multinational companies to improve software quality assurance. TheySay, a company formed by Pulman based on innovative Oxford research in computational linguistics, was acquired by the global software company Aptean in 2017. DeepMind acquired the AI spinout Dark Blue Labs in 2014. Waymo recently acquired the spinout Latent Logic as part of a plan to base its first European engineering hub in Oxford. Research in Foundations, Structures, and Quantum is having industrial impact through a collaboration with Cambridge Quantum Computing (CQC), with the ZX-calculus introduced by Coecke with Duncan of the CQC now a key enabling technology for CQC's quantum compiler, *t|ket*. New hire Kissinger has also worked on applications of ZX-calculus, and the collaboration will be encouraged by the establishment of CQC offices in Oxford. The Virtual Assay modelling and simulation software developed by the Computational Biology theme is commercially licensed to major pharmaceutical companies and is already having impacts on process and production.

Contribution to governance and public policy. The *Global Cyber Security Capacity Centre*, led by the Security theme, has developed a Capacity Maturity Model in partnership with the World Bank that has been used by more than 80 countries in over 110 reviews during the period to benchmark cybersecurity capacity and inform national cybersecurity strategy. Members of our HCC theme have had significant impact in advancing the open data agenda in government, providing leadership in developing the potential of the web, and informing AI and data protection policy. Shadbolt has advised government on open data throughout the period, for example in his roles on the Public Sector Transparency Board (now Data Steering Group) and on the Government's Digital Advisory Board, as well as through the work of the *Open Data Institute*. Jirotko's ESRC-funded project *Digital Wildfires* led directly to her appointment as a specialist advisor to the House of Lords (HoL) Select Committee on Communications, helping to produce its report on *Growing up with the Internet* (2017). She is also on the Steering Committee of the All-Party Parliamentary Group (APPG) on Data Analytics; and gave evidence to the APPG on AI and to the HoL Select Committee on AI (October 2017). Wooldridge also gave evidence to the HoL committee. Binns, Flechais, and Van Kleek have been funded by the Information Commissioner's Office (ICO) to undertake work on the future of data privacy in smart homes. In 2018, Binns became the first Postdoctoral Fellow in AI at the ICO, taking up a two-year fellowship before re-joining the Department in 2020. In July 2019, he gave evidence to the Joint Committee on Human Rights for its report on the *Right to Privacy (Article 8) and the Digital Revolution*. Research relating to privacy in the context of mobile and smart devices (Binns,

Shadbolt, Van Kleek) has informed UK and EU regulator and policy reports.

Public engagement with research. Our academics regularly disseminate their research and address topical themes for public audiences, for example at festivals such as Hay, Cheltenham Science Festival, Edinburgh International Book Festival, and others. Over 2,500 festival-goers attended events run by Oxford CS academics at Hay in 2017 and 2018. Wooldridge and Shadbolt have spoken frequently in connection with their popular general-audience books, *Artificial Intelligence: A Ladybird Expert Book*, and *The Digital Ape*. Shadbolt chaired the 2019 Royal Society Book Prize panel. Our academics regularly contribute to high-profile radio and television programmes, such as Today and In Our Time.³ Our staff benefit from support and training for public engagement provided by MPLS, and we employ a communications officer who produces our bi-annual newsletter, *Inspired Research*, and provides content for our website, highlighting and explaining our research.

4.2. Contribution to the Research Base

Our staff have contributed actively to interdisciplinary research, sustaining the discipline and influencing working practices in the wider research base. For example, the HCC theme provides leadership of the EPSRC-commissioned and funded *Observatory for Responsible Research and Innovation in ICT*, which provides training and tools for improving understanding around the responsible development and implementation of technology. It has already trained over 500 staff and students and is expanding operations to spin out soon as a not-for-profit social enterprise. Shadbolt undertook an independent review of Computer Sciences degree accreditation in 2015–16, commissioned by the Minister of State for Universities, Science, Research, and Innovation. Beyond the discipline, our Computational Biology and Health Informatics theme is working with partners in the pharmaceutical industry (see above), pioneering applications of *in silico* modelling which are influencing medical research practices. Rodriguez's group has twice been recognised for this work, in 2014 and 2017, by the award of the top international prize of the NC3Rs. As documented below, staff across all our themes have also been active in supporting the research infrastructure.

Working with funders. Our staff have helped sustain the discipline through the provision of peer review and strategic advice to funders. Examples include: Gavaghan (Chair, EPSRC Research Software Engineering Fellowship Panel, 2018; BBSRC Training and Fellowships Committee, 2013–16); L. Goldberg (ERC Consolidator Grant panel PE6 CS and Informatics, 2015, 2017); Jirotko (RCUK Digital Economy Programme Advisory Board, 2017–20); Kwiatkowska (REF2021 Subpanel 11 CS and Informatics; Chair, ERC Starting Grants Panel PE6, 2012–16; Royal Society URF Panel; Royal Society Dorothy Hodgkin Fellowships Panel, 2012–18); Melham (EPSRC Cross-SAT/SAN Working Group for Quantum Technologies, 2017–present; Strategic Advisory Network, 2011–17); Rodriguez (Wellcome Trust Basic Science Interview Committee, 2015–20).

External advice. Another significant contribution by members of this UoA involves the provision of external advice to other scientific organisations, and regulators. Examples include: Gavaghan (Chair, External Advisory Board, Software Sustainability Institute, 2013–17); Jirotko (Steering Committee, APPG on Data Analytics, 2018–present); Kwiatkowska (Scientific Steering Committee, Isaac Newton Institute, 2015–17); Melham (Non-executive Director, Alan Turing Institute, 2018–present; Review Panel for Dagstuhl, 2016–17); Ong (Academic Research

³ P vs NP, in which L. Goldberg participated, was voted one of the top ten editions of In Our Time by BBC Radio 4 listeners.

Council, Ministry of Education, Singapore, 2013–present); Rodriguez (Advisor, *In silico* cardiac modelling working group, USA Food and Drug Administration, 2013–present).

Our staff contribute to the scientific direction of the discipline in numerous ways. Examples include:

Chairing scientific associations. L. Goldberg (Vice-President, EATCS, 2016–20); Ong (Vice-Chair, ACM SIGLOG, 2014–18); Gibbons (Vice-Chair, ACM SIGPLAN 2012–15).

Editors-in-Chief. Gibbons (J. of Functional Programming); L. Goldberg (J. of Discrete Algorithms, 2014–17); Gottlob (Logic Journal of the IGPL); Horrocks (J. of Web Semantics); Kroening (Formal Methods in System Design); Kwiatkowska (Joint Editor-in-Chief, ACM Books series).

Journal editorial boards: ACM Trans. Comp. Log.; ACM Trans. Economics and Computation; ACM Trans. on the Web; Artificial Intelligence; Automatica; Formal Asp. Comp. J.; Formal Meth. in Sys. Design; Inf. and Comp.; IEEE Trans. on Soft. Eng; Inf. and Comp.; J. of AI Research; J. of Autonomous Agents and Multi-Agent Systems; J. of Comp. and Sys. Sci.; J. of Log. and Comp.; J. Symb. Log.; J. of the ACM; Pharmacology and Therapeutics; Phil. Trans. of the Royal Soc. A; PLoS ONE; Royal Soc. Open Sci. J.; Sci. of Comp. Prog.; SIAM J. on Comp.; SIAM J. on Disc. Math.

Conference steering committees. Benedikt (ICDT); Gibbons (ICFP 2012–19, POPL 2016–19); L. Goldberg (ICALP); Kroening (CAV, FLoC); Kwiatkowska (FLoC); Ong (FoSSaCS 2009–18, ICALP 2018–22, LICS 2015–17); Ouaknine (LICS); Santhanam (CCC, 2017–20); Staton (LICS); Wooldridge (President, IJCAI Board of Trustees 2015–17).

Conference chairing. Benedikt (ICDT'17); Elkind (AAMAS'19, ACM EC'18); Gibbons (ICFP'17); Kroening (CAV'15); A. Martin and Martinovic (General Chairs, ACM WiSEC'14 and RFIDSec'14); Murawski (FoSSaCS'17); Olteanu (Vice-Chair, ACM SIGMOD'17); Ouaknine (LICS'17); Wooldridge (IJCAI'15); Worrell (MFCS'18).

Conferences hosted by the Department include FLoC'2018 (2,000 attendees) and ICFP'15 (600 attendees).

4.3. Indicators of Esteem

The following external rankings, fellowships, prizes, and speaking invitations provide evidence of the quality of, and recognition for, our research.

External rankings. In the *Times Higher Education World University Subject Rankings*, the University of Oxford placed 1st, 4th, and 1st for Computer Science in 2018, 2019, and 2020 respectively. In the *QS World University Subject Rankings*, Oxford placed 7th in the world for Computer Science and Information Systems in both 2017 and 2018, 6th in 2019, and 5th in 2020.

Fellowships. FRS (Kwiatkowska, 2019; Shadbolt, 2017); Fellow of the ACM (Abramsky, 2014; Kwiatkowska, 2019; Wooldridge, 2015); Academia Europaea (L. Goldberg, 2014; Ouaknine, 2020; Wooldridge, 2015); Royal Society of Edinburgh and Royal Academy of Engineering (U. Martin, 2017).

Awards. ACM Alonzo Church Award (Abramsky et al., 2017); ACM SIGPLAN Achievement Award (Cardelli, 2015); BCS Lovelace Medal (Abramsky, 2014; Gottlob, 2017; Kwiatkowska,

2019); CAV Award (Kroening, 2018; Yang, 2016); NC3Rs International Prize (Rodriguez, 2014, 2017); Royal Society Milner Award (Kwiatkowska, 2018); Turing Award (Berners-Lee, 2016).

Best-paper awards. Abate (QEST'16); Abramsky (LICS'18, test of time); Benedikt (ICALP'17), (ACM PODS'15, test of time); Ceylan (ICDT'20); Cremers (ESORICS'17); De Freitas (ICLR'16); L. Goldberg (IPEC'17); Galanis+ (ICALP'16); Gottlob+ (ACM PODS'19 test of time); Grigore+ (PLDI'14); Kaminski+ (IJCAI'17); Kaminski+ (ICDT'16); Koutsoupias (ICALP'15); Kroening (CONCUR'15); Olteanu (ICDT'19); Staton+ (POPL'19, Facebook award); Ouaknine+ (ICALP'14); Pouly (ICALP'16); Rasmussen+ (NDSS'14); Santhanam (LATIN'18); Staton (ETAPS'17); Whiteson (AAAI'18); Wooldridge (IFAAMAS influential paper, 2018); Zhang+ (AAMAS'20).

Doctoral thesis awards. BCS/CHPC (D'Osualdo, 2016); EurAI (Peters, 2019); NC3Rs (Britton, 2014); Victor Lesser (Peters, 2019).

Plenary invited talks. Benedikt (DL'14, PODS'18); Coecke (CSL'18); Elkind (CIAC'19, FSTTCS'17, SAGT'18); L. Goldberg (ISAAC'19, LATIN'18, MFCS'18, STACS'19); Gottlob (IJCAI'17); Jirotko (CQIS'18); Kiefer (ICALP'20); Kwiatkowska (CAV'17, CONCUR'19, ICALP'16); Olteanu (ICDT'19); Ong (LICS'15, LICS'17, SAS'14); Ouaknine (CCA'19, CONCUR'19, FoSSaCS'17); Staton (ICALP'18, MFPS'15); Worrell (CONCUR'15, FSTTCS'15, ISSAC'17, LICS'19).