REF2021

Institution:
University College London (UCL)

Unit of Assessment:
UoA11 Computer Science

1. Unit context and structure, research and impact strategy

Our research environment is among the best in the world for Computer Science (CS). We are surrounded by world-leading scholars in science, engineering, humanities and the arts. Our location in the heart of London gives us access to many other world-leading academic and non-academic institutions and activities. This is vital for CS, as our field is one that relies on applicability; it draws on and contributes to a wide range of other disciplines and fields of human endeavour. Our cross-disciplinarity is sustained by strong central support from UCL and the Faculty of Engineering, managing expansion and development, and an outstanding infrastructure, enabling us to attract substantial funding and high levels of engagement from all sectors. Our research is informed and developed by rich interactions with industry, policymakers, government, schools and the general public.

We have a strategic vision of our distinct role in the development of the international research agenda in experimental CS that informs all our activities. We are a key partner for many other departments across UCL, offering the ability and willingness to create new syntheses of ideas, to push the boundaries of existing intellectual endeavour and to collaboratively create interdisciplinary and, ultimately, transdisciplinary centres of excellence. This is reflected in our leadership of a wide-ranging set of UCL centres from which we and others benefit. Their diversity of focus, vision, tools and perspective enables us to overcome artificial disciplinary boundaries in seeking to address problems of global significance.

1.A. Structure

To a significant extent our UoA directly corresponds to UCL's Department of CS, which submits 106 staff to REF2021. We also submit staff who are part of our collaborative sphere and integrated into our community: two from the Department of Information Studies; one from the Gatsby Computational Neuroscience Unit; and five from the Division of Psychology and Language Sciences, who are integrated in UCL Interaction Centre (UCLIC). Our submitted FTE rose from 75 for REF2014 to 100.4.

Our 12 groups and 13 centres (Figure 1) create an environment that structurally embeds diversity of perspective founded on disciplinary strength. Research **groups** focus on specific sub-disciplines within CS, while **centres** are intellectually cross-cutting, inter-disciplinary homes for coordinated research programmes involving CS staff and other departments/institutions. While groups provide focus on coherent investigation of sub-disciplines, centres are bridges, formalising strategic intra- and inter-departmental partnerships.

This ecosystem is collaborative by nature. Both groups and centres reflect our multifaceted portfolio, and draw from the rich UCL environment to drive the cross-pollination of ideas. Each group and centre has a leader who is internationally eminent and who evolves strategy, coordinates recruitment and manages members. CS can readily use its scale in forming new partnerships and activities. For example, we identified a number of grand challenges for CS, and were able to mobilise collaborative effort in addressing these (Figure 2).
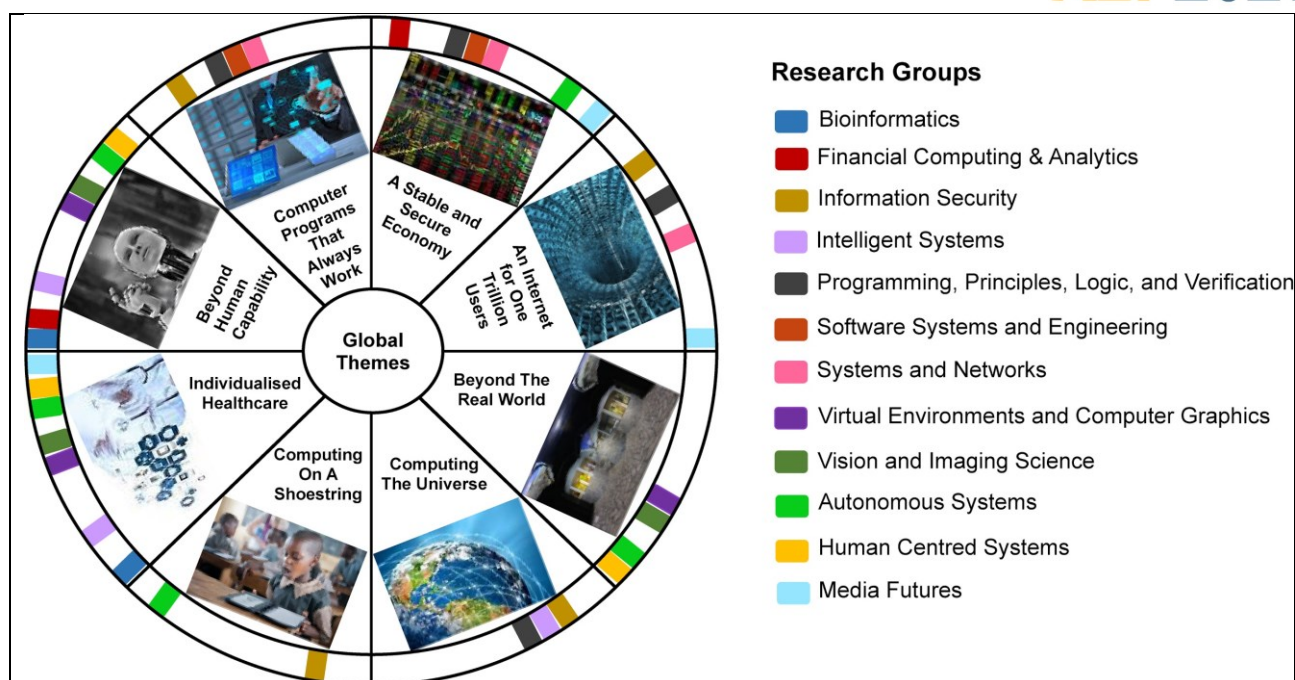
Figure 1: Research Groups and related trans-departmental Centres. Edges denote joint staff membership.
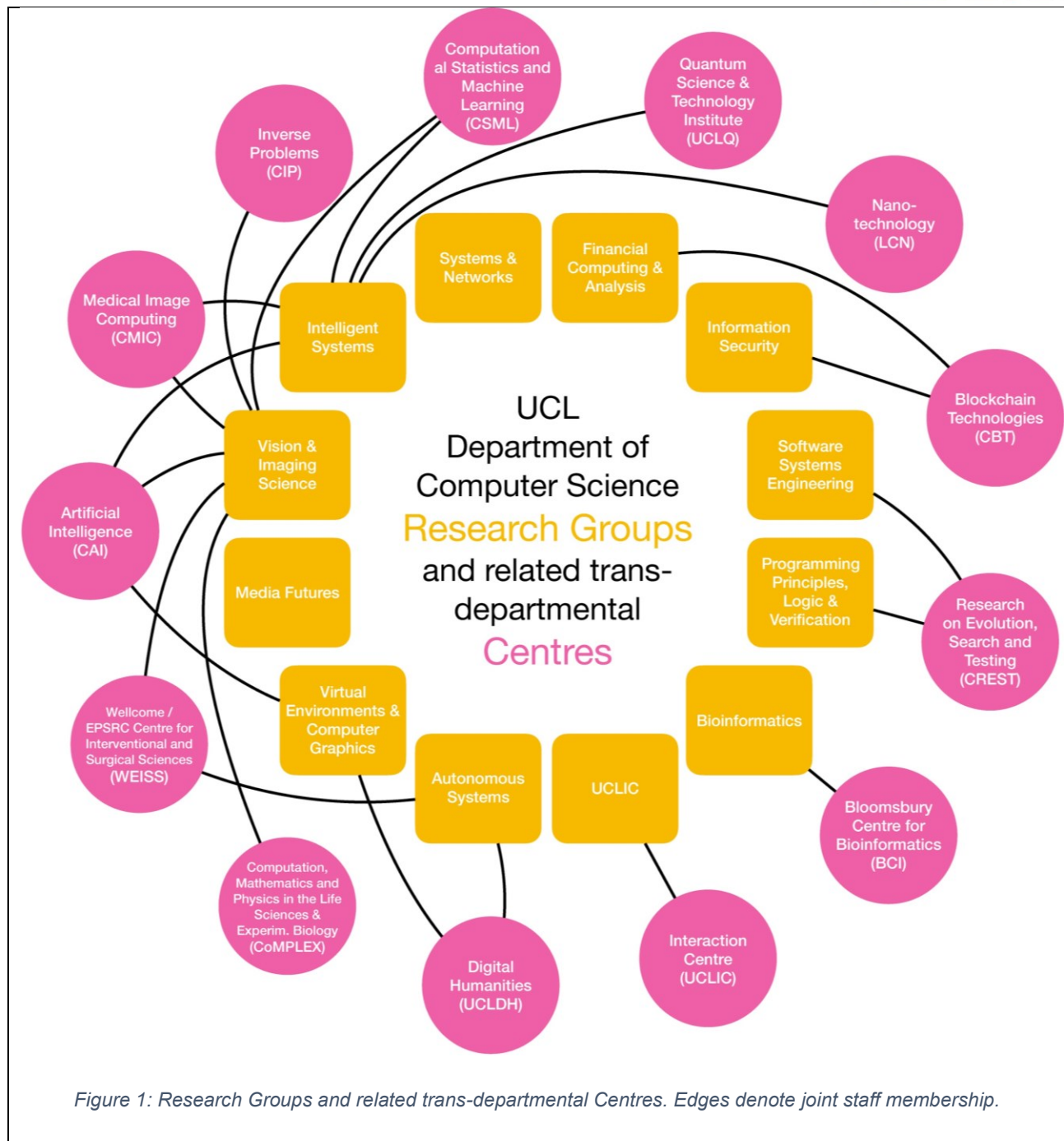
Figure 2: The eight global research themes within UCL-CS and related research groups.

Our centres are located within the department's physical estate while other centres are distributed across a number of departments or link with other institutions, to ensure maximum effective synergy between their partners.

1.B. Research Strategy

Leadership by scholars for scholars

It is UCL's policy that all its leaders, from Provost to heads of groups and centres, are scholars first and managers second. This has a profound effect on UCL generally, and on UCL-CS in particular: two of the past three Faculty deans are world-renowned computer scientists, with one of them now serving as Chief Scientific Adviser for National Security to the UK Government. For most of the REF period, our HoD was Prof John Shawe-Taylor, a world-leading scientist who vacated his position to accept the UNESCO Chair in Artificial Intelligence (AI). His place has been taken by Prof. Stephen Hailes, who has a background in foundational engineering and strong interdisciplinary links. His remit is to continue to ensure the strength of our existing activities whilst leading the identification and development of new (disciplinary and interdisciplinary) opportunities for the future. Leadership at UCL is founded on the development of intellectual and strategic cases, which motivates all our activities. For example, recruitment and promotions are based on scientific and engineering merit, and support is given to initiatives that are intellectually exciting, innovative and imaginative, rather than those that will accrue the highest immediate financial reward.

Experimentation grounded in theory

Our research is underpinned by a symbiotic relationship between theory, experimentation and empiricism. Our shared experimental orientation emphasises measurement, methodological rigour and ultimately reproducibility. Not only does this bind together our research but it determines our strategy, guides our recruitment policy, directs our investment and underpins our research education. We are an established world-leading centre for research in experimental CS. Over the course of the

REF period, we were able to consolidate that success, with our department's position in the QS World Rankings for CS rising from 25th in 2014 to 17th in 2020 (4th in the UK).

Our distinctive intellectual position as a focus for experimentation grounded in theory requires wide coverage of the CS intellectual landscape. This ensures that we draw on appropriate theory (derived from multiple sub-fields). It allows our experimentation to be conducted in real world settings. Our large size enables sustained development of a diversity of links between CS research and the many other leading centres of research activity within UCL and internationally.

Strategic plans

Our strategic plans are developed and refined with awareness of and respect for the REF cycle but are not dominated by it. The number of academic staff in the department has increased by 36% over the REF period (from 76 to 103), a result of strategic investment that flows from a recognition of the importance and potential of CS.

Plans described in our REF2014 submission set the direction and scale of growth, but we have also **grown in response to emerging topics** such as AI and have responded agilely to capitalise on our capabilities in this rapidly developing area. We made a coordinated investment in core machine learning, computer vision, graphics and natural language processing, leading to the establishment of the UCL AI Centre. We have also significantly expanded Information Security; eight new appointments were made strengthening and broadening the group's expertise. Similar growth has been made in the PPLV group, and we are in the process of further developing the links between the PPLV group and both the UCL Quantum activities and the Department of Philosophy. We have recently hired a major team led by Sriram Subramanian working on innovative displays, haptics and multisensory Interfaces; they joined the UCL Interaction Centre (UCLIC) creating the largest centre of HCI research activity in Europe.

Inspired by the Faculty's strapline 'Change the World', the department has established a GCRF group that coordinates and promotes research that can impact the lives of people in developing countries. This has prompted specific success with **Global Challenges Research Funding (GCRF)** calls and establishing collaborations with UNESCO and WHO, as well as developing a broader strategy to maximise the potential impact of its research in developing countries; see Section 3, Large grants and strategic awards. John Shawe-Taylor's appointment as the first UNESCO Chair of AI reinforces our international agenda. He spearheaded the UNESCO COMEST group to draft a proposal for UNESCO recommendations around the ethical use of AI, subsequently accepted in the November 2019 assembly of UNESCO. He has also been collaborating with the newly approved Category 2 UNESCO Centre for AI in Slovenia (IRCAI). His charity, "Knowledge 4 All Foundation" (K4All) has helped champion a UNESCO recommendation promoting the use of open educational resources (OER)s. K4All is active in a number of projects with UCL promoting both the exploitation of OERs in education (see x5gon.org) and the development of a network of AI Researchers and practitioners in sub-Saharan Africa.

We have also built strong **strategic alliances with industrial partners** and co-developed the Portico Ventures Programme with UCL Business, allowing CS researchers more freedom to take their ideas to market through spinouts. The creation of the strategic alliances team (SAT) has enabled more industrial links to be established agilely, including helping the Financial Computing and the AI Centre to build and maintain strong links with companies such as Google Deepmind, Facebook (FAIR), CISCO, Amazon and Adobe. Strategically, this has raised our profile of innovation to be a third pillar, alongside research and teaching.

During this REF period, the department has been developing plans with UCL Estates for **bespoke new premises**. A site has been identified and an outline design completed, the project has been added to UCL's major project portfolio, and financial models are currently being finalised. The development combines: a new building for CS, in which our strategic mix of research, teaching and innovation is core to the design; space for a new UCL Institute of Interdisciplinary Computation, creating a physical space for new interdisciplinary collaboration; and student residential accommodation that can be repurposed for conference accommodation when not used.

In the interim, we have acquired a floor of 90 High Holborn (1,921m^2), housing CMIC and the new AI Centre with space for 218 staff, and 169 Euston Road (1,850m^2), which will host offices and labs for various groups, including UCLIC, VECG, InfoSec, Financial Computing, with a total headcount of 140. Refurbishment of the latter has been delayed due to COVID-19.

The department has been instrumental in helping shape the new **UCL EAST** development on the Queen Elizabeth Olympic Park complex. This will house both the GDI Hub (currently at Here East) and a new Robotics and AI centre that will see the hiring of a further ~24 academic and teaching staff from 2021, further developing robotics activity within the department. We have recently hired two junior academics in robotics working across both our Bloomsbury and Here East campuses to complement existing staff.

1.C. Mechanisms for strategic planning

Institutional-level support and strategy

UCL has provided extensive support for our research via central research facilitation officers to support applications for large grants, such as Horizon 2020, ERC, CDT/DTC and charity or research council programme and platform grants. Centralised mechanisms for organising mock interviews have substantially increased success rates. Large grants are routinely supplemented by centrally funded studentships, typically one fully funded per £1M of award. Many of our staff have benefited directly from pump priming research/innovation support from central funds such as the UCL Grand Challenges small grants and special initiatives: French Embassy collaborative science and technology workshops (Alexander 2016 £10K); UCL Knowledge and Innovation funds (Hailes 2020 £15K; Alexander 2017 £15K); a total of £1.2M from UCL-EPSRC Impact Accelerator Innovation and Enterprise funds distributed over 35 projects; UCLH Biomedical Research Centre pump-priming awards (Drobnjak 2019 £50K; Parker 2019 £50K); Capital Equipment fund for a hyperpolarised-xenon imaging device (Parker 2019 £400K); UCL-MRC skills development fellowship (Wijeratne 2019 £250K).

External Relations

Over the REF period, the department's External Advisory Board included the following members: Prof Mandy Chessell (Chair), IBM; Dr Philip Bonhard, Accenture; Dr Reza Hazemi, Deloitte; Dr Andrew Herbert, former Chair at Microsoft Research; Aideen O'Brien, Morgan Stanley; Lesley Payne, Nuffield Health; Dr Paul Phillips, Causata; Dr Geoffrey Taylor, SAS; Dr Richard Wheeldon, Cisco; Dr Jason Kingdon, Blue Prism.

A significant recommendation of the board was to forge better and more links with industry. To this end, a **Strategic Alliances Team (SAT)** was created in the department, comprising three full-time members of staff with strong industry and industry-liaison experience. This resulted in significantly more regular contact with key industry partners, ranging from large world-leading organisations (see

Section 4). Consequently, we have seen new streams of funding for research built around shared strategic priorities, joint labs, and spinout opportunities, as well as substantial engagement in our programme of education. The SAT has created a tiered model of engagement to support 35 strategic industry partners (Tier 1), 83 collaborator industry partners (Tier 2) and over 150 supporter industry partners (Tier 3). Relations with spin-outs are also strengthened, with CS staff and students actively collaborating with 26 founders (Tier 4).

The SAT oversees external engagement at three levels: strategic research collaborations with industry, teaching and student related engagements covering student projects, placements (IXN) and internships (NXI) and, lastly, the engagement related to commercialisation and knowledge transfer that includes the relationships with the department's spin-outs ecosystem. The SAT also curates impact information and links together colleagues, cutting across sub-disciplinary boundaries.

A new **External Relations Committee** was formulated with a remit, both to define departmental strategy for maintaining, growing and deriving value from external relationships across all aspects of our operation (including research, education, innovation, alumni), and to oversee the operationalisation of that strategy. The first meeting of this committee was explicitly delayed from Q2 2020 to Q4 2020, given pandemic prioritisation; the committee has been fully since.

Strategic research fund

Our yearly fund, which has an indicative budget of £100k, was established by the department for small proof-of-concept projects. It has pump-primed initiatives that were too premature for external investment; awards averaged at £3,600, with individual awards having been as high as £49k, where multiple staff benefitted from the investment. Over the REF period, the fund paid out 104 small grants totalling £324k.

Strategic Planning Retreat

The department's academic staff attend biannual planning retreats. These help to ensure that all staff contribute to and support strategic plans for our research. The retreats also enhance collaboration between our groups and centres and have helped to inspire synergetic projects that define CS grand challenges.

1.D. Achievements and strategic development and expansion of groups and centres

Our department's activities are wide-ranging; each research group contributes uniquely to our portfolio. We now introduce our groups, highlighting aspects that illustrate their contribution.

Autonomous Systems (AS)

Established in 2015, AS conducts research on theoretical, computational and experimental aspects of autonomous systems, from sensing to learning and decision making, across a wide range of real-world domains. The group has world-leading expertise in the area of decentralised data fusion, high-performance state estimation, and statistical models of uncertainty, with direct applications to map building and navigation, space missions and, more recently, robot locomotion and manipulation in natural uncertain environments. The group regularly collaborates with world-leading industrial partners in the area, such as BAE Systems and NASA Ames, as well as smaller local companies (e.g., MoSys Ltd). Members of the group co-founded the company KIT-AR, https://www.kit-ar.com/, whose smart manufacturing technology is based on the group's research work on sensor fusion and

scene understanding. AS is also renowned for its interdisciplinary work, having built new sensing devices and deployed them on wild animals, working with veterinarians to develop new knowledge of how such animals navigate in their environment. The group is part of a strategic investment of the department and UCL in the Robotics and Autonomous Systems area, and its staff contributing to the newly established MSc Robotics and Computation.

Bioinformatics

This group is internationally recognised for its work in applying machine-learning algorithms to problems in biology and medicine, and for the BBSRC-funded PSIPRED Workbench, a set of freely available Web-based bioinformatics tools. The service is used by biologists 500–600 times daily and has recently been awarded ELIXIR-UK Node Service status in recognition of its importance in the field. Research highlights from the group include applying deep learning to protein structure, large-scale machine learning systems to predict gene function, applications of machine learning to cancer informatics data and applying DCNNs to interpreting microscopy images. This work has been published in top-tier journals including Nature and Cell, and Professor Jones regularly appears on the **Clarivate Highly Cited Researchers List**, including the most recent list published in 2020. The group is supported by the ERC (Advanced Grant), BBSRC, Wellcome Trust and CRUK. Industry links include consulting on Google DeepMind's AlphaFold project and research contracts from Pfizer Inc. (on deep learning-assisted protein modelling) and Elsevier BV (gene function prediction).

Financial Computing & Analytics (FCA)

FCA investigates socio-economic systems using tools from statistical physics, network theory, and CS. FCA research is laying the foundations for the study of the new digital economy at the interface between technology and society. The group's work is of importance to regulators, policymakers, the services industry and citizens. FCA researchers collaborate with the private and public financial services sector including investment banks, retail banks, central banks, regulators, hedge funds, financial services technology firms, insurance companies, reinsurance companies, stock exchanges, alternative trading and execution venues. The group supports the **DTC in Financial Computing** that has produced over 100 Ph.D. students since its creation. FCA group also supports two master programmes in Financial Risk Management and in Computational Finance which have been ranked among the top five in the world. Furthermore, two new master programmes on the digital economy and financial technologies started in 2021. The group trains about eighty postgraduate students per year and has an average of 3 research associates. In 2015, the group members were at the core of the creation of the **UCL Centre for Blockchain Technologies (CBT)** that is the world-reference centre in this domain. The centre has over 200 associates and is running research initiatives together with the faculty of laws, the departments of economics, political sciences, social sciences and the Bartlett.

Information Security (InfoSec)

This group is leading in Cyber Security Research, nationally and internationally. It is recognized as an **Academic Centre of Excellence in Cyber Security Research** by EPSRC and NCSC, hosts one of two **Centres for doctoral training in Cybersecurity**, and is a key part of the **National Research Centre on Privacy, Harm Reduction and Adversarial Influence Online (REPHRAIN)**. Group members regularly publish in, serve on program committees of, and deliver keynotes at, top security and cryptography conferences. They have secured regular national and EU research funding and research gifts from top technology companies (Google, Facebook, Amazon, Xerox, Nokia, etc).

InfoSec has established expertise in human, organisational and economic aspects of cybersecurity, that have impacted national-level policies and advice on cybersecurity, as well as cryptography, privacy, distributed ledgers and Blockchain, measurements, and online harms. Members of InfoSec have co-founded, and have seen technologies developed in the group be used by, a number of start-ups (Chainspace, which was later acquired by Facebook, Nym, Difinity, etc.) and contributed to national cybersecurity initiatives, such as editing the NCSC Cyber Security Body of Knowledge.

Intelligent Systems (IS)

This is a world-leading research group in AI with many substantial theoretical and applied contributions in machine learning, computational statistics, natural language processing, computational models of argument, and quantum information. The group co-founded the **UCL AI Centre** in 2019 to facilitate foundational research, and collaboration across the college. It runs the UCL **CDT in Foundations of AI** with £6.7M UKRI funding and £5M industry funding, and the UCL **CDT in Delivering Quantum Technologies** (2019–2024). IS works closely with the UCL Gatsby Computational Neuroscience Unit and UCL Dept of Statistical Sciences through the joint **UCL Centre in Computational Statistics and Machine Learning (CSML)**, whose director Arthur Gretton is part of our UoA. We are lead partners (with London Centre for Nanotechnology) on the EPSRC Prosperity Partnership in Quantum Software for Modeling and Simulation award (£5.4M joint with University of Bristol and Google). IS is closely involved with leading tech companies. For example, Silver led the **AlphaGo** projects at DeepMind with Graepel, both UCL joint appointments; IS recruited the DeepMind chair Deisenroth and is hosting the first UK cohort of Facebook AI Research PhD studentships. New appointments strengthen research in machine learning (Kusner, Paige and Ciliberto), NLP (Stenetorp and Rocktäschel), quantum information (Masanes), and ML/AI for healthcare (Przulj and Fernandez-Reyes). With the College of Medicine of the University of Ibadan, Nigeria, the group created the interdisciplinary **African Computational Sciences Centre for Health and Development** to develop AI to address challenges in sub-Saharan countries. We also have a partnership (led by IS's Benjamin Guedj) with Inria, see Section 4.B. Further successes come from the appointment of Shawe-Taylor as *UNESCO Professor of AI*, the award of the *ACM Prize in Computing* to Silver, and the award of the *London Mathematical Society Whitehead prize* to Cubitt.

Media Futures (MF)

MF are internationally known for frameworks for information retrieval, multi-agent reinforcement learning, complex networks and online social media analysis, particularly analysis of users' digital trails (web searches) to infer user and population health. The group members, 3 Professors and 1 Associate Professor, bring both strong academic and theoretical knowledge as well as deep commercial experience. Cox (Head of Group) was awarded the 2019 *Tony Kent Strix Prize* for contributions to Information Retrieval. Yilmaz received the 2015 *Karen Sparck Jones Award* for advancing the field of Information Retrieval and Natural Language Processing. Yilmaz was also awarded a 2017 *EPSRC Fellowship*, is *Elected Member for ACM SIGIR Executive Committee* (2016–18) and received a *Google Faculty Research Award* in 2014 to support faculty members working on problems that will impact how future generations use technology.

Programming Principles, Logic & Verification (PPLV)

PPLV conducts world-leading research in logic (philosophical, mathematical, and computational) and algebra (especially category theory) and their applications to the semantics, specification, and verification of programs and systems. The group comprises full-time 8 faculty members (though Pym,

Head of Group, also has roles in UCL's Philosophy Dept., in UCL's Information Security group, and in the Institute of Philosophy) and includes also O'Hearn (joint with Facebook), Cook (joint with Amazon, AWS Director of Automated Reasoning), and Alglave (joint with Arm, where she is responsible for the memory model). O'Hearn's, Cook's, and Alglave's joint appointments have been vectors for PPLV's work to have profound industrial impact through tools (such as INFER and Herd) for program analysis and network and chip verification. The group, which is supported by many very substantial research grants from bodies including UKRI, the EU, the ERC, and industry, includes a large, lively, and diverse community of interacting PhD students and postdoctoral staff, whom we endeavour to develop into substantive roles both within and outwith UCL. Silva received a *Philip Leverhulme Prize* in 2016, the 2017 *Presburger Award*, and the 2018 *BCS Needham Award*. Alglave received the 2020 *Needham Award*. O'Hearn became an *FREng* and an *FRS* and received the 2016 *Gödel Prize*. Cook became an *FREng*.

Software Systems Engineering (SSE)

The SSE group is internationally renowned for its pioneering and impactful research. SSE has led the adoption of search-based optimisation, transforming software engineering, and pioneered radical new ideas, such as applying genetic improvement to software, applying information theory to software engineering, and analysing code as a natural language. In 2019, Facebook adopted Sapienz and Sapfix, two of SSE's automatic testing and repair tools, and is now running them at scale. SSE's work on time-travel debugging was distributed in Microsoft's Edge browser. SSE has enjoyed substantial funding success, winning over £5M and £500k from industry. In 2019, Harman received both the *IEEE Harlan D. Mills* and the *SIGSOFT Outstanding Research* awards. Since 2015, SSE has welcomed four outstanding academics. Petke holds an *EPSRC Fellowship*. Mechtaev won the prestigious *SIGSOFT Outstanding Dissertation Award* in 2019. Jia founded a startup that Facebook acquired. Federica progressed to full professor in 3 years. SSE runs the internationally renowned **CREST Open Workshop series** that has, over 10 years, brought more than 800 world-renowned researchers to UCL to present and discuss their work.

Systems and Networks

The group is internationally renowned for its contributions to algorithms, protocols, and systems that underpin the Internet; to network and computer systems security; to wireless networks; and to large-scale distributed systems. The group has pioneered the design of practical multi-path transport and congestion control for the Internet and data centres, culminating in standardisation of Multipath TCP and subsequent deployment by Apple in iOS (see REF3). The group has made significant practical advances in online privacy: COWL, which protects sensitive web data from malicious JavaScript, has received significant attention in the **World Wide Web Consortium (W3C)**, the standards body for the web. The group advanced wireless system capacity: by improving the efficiency of interaction between TCP and WiFi's MAC layer, and by cooperatively reducing interference among densely deployed WiFi access points. Handley recently received the *ACM SIGCOMM Award* (2019) and was made a *Fellow of the Royal Society* (2019) for career-long high-impact achievements in Internet multicast, telephony, congestion control, and open Internet standards and open-source systems in these areas. Vissicchio received the *IRTF Applied Networking Research Prize* (2015) for work on achieving the flexibility of Software-Defined Networking (SDN) switches on legacy IP routers and routing protocols.

UCL Interaction Centre (UCLIC)

UCLIC is a cross-departmental centre, drawing members from the departments of CS (forming the eponymous UCLIC group) and psychology (also returned through this UoA). It is internationally leading in HCI theory and user-centred design methods. In particular, it is known for advancing conceptual frameworks based on experimental and in-the-wild studies; on behavioural change, cognitive and affective modelling, collaborative learning, information interaction, physical computing, smart cities and digital healthcare. Because of its international reputation, UCLIC has grown considerably in size over the last 7 years, now comprising 15 faculty, including recruiting Subramanian, holder of 2 major awards and 4 grants (total £2.5million). In addition, Subramanian was awarded a *Royal Academy of Engineering Emerging Technologies Chair*. Rogers (UCLIC director) was recognised as a *Microsoft Research Outstanding Collaborator*, awarded an *MRC Suffrage and Science Laureate Award*, and elected as an *ACM Fellow*; Blandford received an *MRC Clinical Sciences Centre's Award* to celebrate women in maths and computing. Holloway was awarded £10M in to set up the **GDI Hub**. UCLIC led the **Intel Collaborative Research Institute (ICRI)**, in collaboration with Imperial (2012–2018), concerned with user-centred and technical exploratory research into sustainable and connected cities ($7.5M). UCLIC has been successful in receiving several large EU/EPSRC grants, e.g., *EPSRC Programme Grant* (CHI+MED, 2009–2016, £6M), collaborating with QMUL, U. Swansea and various hospitals. UCLIC contributes HCI expertise within substantial interdisciplinary grants such as the **i4health CDT** and the **WEISS (Wellcome Trust / EPSRC) Centre**.

Virtual Environments & Graphics (VECG)

VECG is known for demonstrating the impact of fundamental computer graphics and real-time multi-sensory systems research through user experiment on novel prototypes. We are well represented at venues such as TOG, SIGGRAPH, TVCG, IEEE VR, Eurographics, ACM CHI, CVPR, ICCV and NeuIPS. The impact of our work is broad: Mitra has founded a **new research centre with Adobe in London**; our work on virtual reality and augmented reality led to substantive collaborations, e.g., through placements at Microsoft Research Redmond (Steed) and Varjo Technologies (Weyrich). Recently, Ritschel, winner of the Eurographics Young Researcher Award in 2014, joined us. He was promoted to Professor in 2019. Yasin also joined us bringing expertise on audio and multisensory integration. Weyrich, founding member of the **UCL Centre for Digital Humanities (UCLDH)**, one of the first and leading DH centres in the world, continued as deputy director. UCLDH runs an advanced digitisation facility for use across arts, engineering and libraries and promotes data science within the humanities, with ties with the **Alan Turing Institute**. Mitra received the *BCS Roger Needham Award* (2015), and the *Eurographics Outstanding Technical Contributions Award* (2019). Steed received the *IEEE VGTC's Virtual Reality Technical Achievement Award* (2016). Mitra and Steed were appointed *ACM Distinguished Speakers*. VECG students won *Eurographics PhD Award 2020* (Aron Monszpart) and *IEEE VGTC Virtual Reality Best Dissertation Award 2018* (Sebastian Friston). Five alumni in academic positions elsewhere.

Vision and Imaging Science (VIS)

VIS is internationally renowned for ground-breaking research in machine learning for vision and imaging, deep generative models, 3D vision, robot vision and inverse problems and has high visibility in all the top computer vision (CVPR, ICCV, ECCV, IEEE PAMI, IJCV), graphics (SIGGRAPH), robotics (ICRA, IROS) imaging science (SIAM) and medical imaging (MICCAI, IPMI, ISMRM) venues. VIS members devised area-defining deep-learning models for multitasking (Kokkinos:

DeepLab, UberNet), unsupervised monocular depth estimation (Brostow: MonoDepth), and human pose estimation (Kokkinos/Agapito: DensePose/Lifting) and long-standing public domain software packages in medical imaging (Camino, NODDI) and inverse problems (TOAST++) with global user base. VIS has extensive collaborations with industry partners including Facebook, MSR, Amazon, Cisco, Siemens, Philips and GSK. VIS has outstanding success in personal fellowship awards and large grants, see Section 3, and chairing top vision and medical imaging conferences (CVPR'16/ICCV'23, ECCV'22, IPMI'15). VIS leads **two new EPSRC Centres for Doctoral Training** secured in 2019: i4health and Foundational AI,see Section 3.

VIS leads the **UCL Centre for Medical Imaging (CMIC)** which provides a vital translational pathway between UCL-CS and Engineering to medicine. CMIC includes over 200 FTE (from 30 in 2005) and 22 affiliated academic staff across engineering and clinical-science departments. CMIC maintains a £30M grant portfolio including £5M in industry contracts. CMIC spawned the **Wellcome/EPSRC Centre for Interventional and Surgical Sciences (WEISS)** in 2017 via a £14M award from the Wellcome Trust and EPSRC to translate emerging research into surgical operating rooms. WEISS has leveraged an additional £80M grant portfolio, includes over 150 researchers, has directly initiated 21 clinical trials, and developed 3 CE approved medical devices.

VIS also leads the **Centre for Inverse Problems (CIP)**, which has members from CS, Mathematics, Statistics, Physics, and the London Centre for Nanotechnology amongst others. CIP is affiliated to the CDT in Data Intensive Science (2019) and attracted new grants of around £2M.

1.E. Strategic aims and goals

Enhancing our capabilities: We will seek investment for new staff to strengthen our existing links with medicine and life sciences. Similarly, we will seek to develop our financial computing activities, building a new cross-faculty UCL Institute, securing the staffing of the CBT and strengthening links to AI. We will invest in quantum computing, building bridges to the theory of computation and beyond. Finally, we will collaborate in developing Advanced Research Computing (ARC), building world-class computational hardware accompanied by research in large-scale computing and research-led service delivery.

Working at scale: the department is as big as some faculties and, aside from planned investment, Robotics at UCL EAST will add significantly to our staff numbers. This necessitates a new structure for CS, initially as a School of Computer Science.

Ensuring coherence: Spatial fragmentation is a challenge and, consequently, we aim to house the department together to improve links between research groups. We will develop innovation space within the department, and a new Institute of Interdisciplinary Computation.

Developing relationships: We will deepen and broaden our relationships with industrial partners, diversifying our income and providing new technical opportunities. We will develop labs for partnerships with industry and with global research organisations, and we will co-develop a UCL Computational Social Science Domain.

Embedding EDI: EDI is core to the department. We have made significant progress in respect of gender, but we will further broaden the aspects of EDI we consider and more thoroughly embed these into the departmental culture.

2. People

2.A. Staffing strategy and staff development

Excellent recruitment and retention

We have recruited 44 internationally leading scholars in the REF period, 14 of whom Early Career Researchers (ECRs). Our excellent staff support and development, with processes that impact our researchers at all stages from pre-PhD to emeritus professor, enabled expansion of the department from the previous REF by 36%. Our recruitment strategy has varied according to opportunities and circumstances. For example, we have made use of proleptic recruitments (converting fellowships into permanent positions), where fellows have demonstrated their research leadership and excellence within their fellowship. This route has enabled us to recruit a number of excellent women, and it has enabled us to enact our strategy of strengthening existing groups, but in cases where we have sought to expand our expertise or open new directions we have made more targeted open recruitments.

The quality of our early-career recruits is evidenced by all of them having passed their probation period. During the entire REF period only 17 academic staff (14%) have left the unit for reasons other than retirement. Staff choose to stay and prosper.

Industrial secondments and collaborations

We support staff interchanges with industry in both directions, ensuring our research is informed by real-world problems and used in industrial applications. A frequent mechanism are sabbaticals and shorter periods of (paid) leave as part of UCL's consultancy allowance. Industrial secondments during the REF period include ARM, Adobe Research, Facebook, Google, Microsoft Research, Mo-Sys Ltd, Nvidia, OutThink, PROWLER.io, Telefonica Research, Varjo Technologies, iProov. Following secondments, several of our staff have transitioned to part-time employment in industry, retaining 0.5–0.2 FTE at our department with an active embedding into our research groups. Examples involve Adobe Research, Amazon Web Services, Ariel, ARM, DeepMind, Designability charity, Deutsche Bundesbank, Digital Surgery Ltd., Facebook AI Research, Facebook Novi, Google, Niantic, OneSpan, OWidgets, PhaseCraft, PROWLER.io, Synthesia Technologies.

Strategic alliances between the department and industry are an essential route by which academic computer scientists can have real-world impact. The practical problems faced by industry working at scale lead to new perspectives on fundamental academic problems which, when followed through in academia, lead to new insights. These insights are not, generally, of sole interest to a particular company and, through publication, we share our developments freely. In all cases where there is a potential conflict of interest, we explicitly negotiate IPR agreements in partnership with the appropriate central UCL function and the HoD actively manages potential conflicts as they arise.

Appraisal, recognition and promotion

All research and teaching staff are automatically considered for promotion each year. This ensures a routine of valuable yearly feedback. In addition to feedback from the promotion round, all staff are appraised at least biannually, which provides an opportunity to review all aspects of work and career, identifying specific stretching objectives to focus work for the next period. This is also the forum within which research quality and integrity is considered.

Nurturing early career researchers and new starters

New recruits are assured that the development of their research careers is a top priority. This is manifested in several ways: allocating start-up funds that can pay for equipment required and support participation in conferences, workshops and other research meetings (budgeted at £7.5k per person for travel/consumables for up to two years, plus any other equipment agreed, which may be considerably higher, based on need); allocating academic mentors to advise on matters affecting their work, from understanding local procedures to taking a strategic view of their research goals; supporting the funding of two PhD studentships (home/EU or overseas) within their first three years; and limiting their teaching to the equivalent of one module in their first year so that they can retain research momentum. This is extended to two years if they are awarded an EPSRC first grant. While EPSRC support was still capped at a level that only supports an RA for 12 months, which we view as inadequate for initiating a significant CS project, we augmented first grants with departmental funding to extend RA hires by a further 6 months.

We recognise the often precarious position of post-docs on short term contracts. We therefore provide training and career development programmes for our RAs, in accordance with the Concordat to Support the Career Development of Researchers. We0 use flexible funding from longer, larger grants to help to retain RAs through the exigencies of specific funding mechanisms.

Sabbatical support on merit not merely accumulated service

Sabbaticals are used to achieve specific goals as outlined in a proposal submitted by the academic concerned, possibly prompted by the outcome of an appraisal. They are allocated on merit as assessed by a sabbatical committee that was formed to ensure objective processing. An applicant need not wait for a pre-scheduled sabbatical. Sabbaticals awarded during the REF period included projects linking into a new area or application domain; visiting professor roles at other universities across the globe (Australia, Europe, New Zealand, Rwanda, Singapore, and USA [Stanford, MIT]); developing links/pursuing commercialisation with industrial partners (ranging from large corporations like Microsoft R&D and Google to small start-ups); writing books; refocusing research after intensive administrative work; and personal situations that have impaired time for research. For instance, staff extended parental leave with both paid and unpaid sabbaticals.

Teaching-only staff

CS employs staff on teaching-only contracts both because they have well-developed expertise in pedagogy that benefits all academic staff and because their teaching (and administration) load is at least twice that of an established academic. This both reduces the time research-active academics spend on teaching and associated administration, which allows them to focus on more advanced modules that draw more heavily on their research expertise and make them visible to prospective PhD students. Teaching-only staff have permanent contracts, carry a Lecturer title and have their own pathway to Professor.

Extensive fellowship successes

Many of our staff have been exceptionally successful in gaining awards of highly competitive fellowships, underscoring the leading nature of our research (see Section 3). For those fellows who are not permanent staff there is a procedure for considering them for a proleptic appointment, a cornerstone of our Athena SWAN mechanisms. Permanent staff may still teach during the fellowship, in exchange for a corresponding reduction once it has expired.

2.B. Research Students

Extensive funding underpinning

We aim for exceptional applicants to CS to secure funding. We define exceptional as having top grades from a leading institution and/or prior publication in a first-tier venue. Increasingly, our successful applicants have both. In addition to the **Doctoral Training Centres (DTCs)** funded by the EPSRC (see Section 3), there are a number of funding routes available. As noted above, some are **funded completely or partially by industry**, e.g., by Microsoft Research, DeepMind or Facebook AI Research. Some of our students are funded by UCL scholarships, and our students regularly secure Amazon, Google and JP Morgan Global **Fellowships** that pay fees and stipend for 2–3 years of their studies. These fellowships also offer fellows an internship with the funding company. At the time of writing, six of our students are active fellows. Partial funding of research students is secured via 29 **IMPACT** and 272 **iCASE studentships** sponsored by organisations like BBC, ARM and GE. We also have departmental, **fully funded studentships**, which are part of the academic recruitment package (Home/EU or Overseas).

Taught research foundations

Throughout the PhD programme, we run **bespoke CS training** that supplements more generic research training **courses offered by UCL**, including by **UCL Innovation & Enterprise**, who target many of their courses specifically to students. Our **DTCs provide specific support** and resources for their own cohorts, but events and training that they provision are usually offered across the department. Lastly, our **specialist MSc and/or MRes courses** also contribute to our graduate student training: by offering our PGRs to co-supervise MSc projects, and to contribute to taught lectures, we help them gaining the necessary experience for academic positions.

Supervision

Each student has a principal and co-supervisor. Supervisory meetings are held at least fortnightly. Annual vivas include an external assessor; our administration team is proactive in ensuring that these take place within the agreed timeframes. Joint supervision of students with other departments brings together distributed research groups and furthers collaborations between CS and other groups across Engineering, and other faculties. Our groups and centres provide formal and informal support to supervisors, from mentoring and technical training to social activities.

Nurturing research student engagement

Students are expected to submit papers to international conferences. There is a departmental budget to ensure that students can attend conferences and other relevant events if there is no specific travel funding allocated to their studentship. We encourage students to attend conferences at which they are not speakers to nurture their wider involvement in their technical and scientific communities. We also encourage research visits, secondments, and engagement with professional bodies and research users. Students develop their engagement and skills through a variety of group activities, such as reading groups, research retreats, events with industry speakers and open events. For example, VECG runs a "VR Club" monthly – a public event, advertised to audiences across UCL and externally, where PhD students and others demonstrate our laboratories.

Placements and secondments

We actively encourage and support students to undertake internships with companies. The Department's DTCs in Foundational AI and Cybersecurity offer 3–5 months internships for PGRs, typically in their second and third year. Beyond that, our PGRs have an excellent track record in obtaining internships, often facilitated by their research group's industry links. Examples over the REF period include visits to tech and communications companies including *Adobe*, *Amazon*, *CISCO*, *DeepMind*, *Facebook*, *Google*, *Imagination*, *Intel*, *Microsoft*, *NICT Japan*, *Sony*, *Telefonica*, *Tesco*, *Ultraleap* and many smaller companies; healthcare industry including *Roche*, *Unilever*; financial service institutions including *Bank of England*, *Barclays*, *FCA*, *PRA*, *Visa* and all major *investment banks*; and governmental research ranging from *BBC Research* to *GCHQ*.

Developing leadership and research organisation skills and experience

We encourage students to become involved in **organising events**. For example, our students arrange half-day departmental student conferences with talks and posters by their peers. As our number of PGRs has expanded, we have introduced a buddy system in which second-year or third-year students mentor first-year students. The scheme is voluntary and student-led, aiming to give students the opportunity to share responsibility.

PGRs nominate representatives for the **staff-student consultative committee** to discuss arrangements for the PhD programme. We also have a PGR on the **Athena Swan Committee** representing students' interests and organising student outreach events.

The Faculty organizes and funds two-day retreats for all first-year PGRs at **Cumberland Lodge** (a residential seminar centre in Great Windsor Park). The schedule involves sessions on team building, presentation skills using theatre techniques, engaging external audiences, and resilience and wellbeing. Plenty of opportunity is given for students from different departments to interact and socialize.

2.C. Equality and Diversity

Promoting and supporting women in CS research

Our departmental strategy is to continue working towards full gender balance at all levels, from school pupils well in advance of arrival through to the most senior professors in the department.

2021 will see the department celebrate a decade of engagement with the Athena Swan programme, led by a highly proactive committee that includes representatives of all grades of staff and students, as well as the senior management of the department, including both its current and its previous head. Over the past decade, our activities have developed and expanded both within the department, and by seeking opportunities to act as a beacon to others. This has been recognised with a number of awards: the department is very proud to have retained the Silver Award in 2020 that we gained in 2015; we were one of the first UK CS departments to achieve this distinction. At the time of writing there are five unitary CS/Informatics departments (rather than collective faculties) with a silver award in the UK and none with a gold. In 2016, the department was also the recipient of the inaugural European Minerva Informatics Equality Award for "its comprehensive gender policy, the diversity of initiatives put in place as well as the strong evidence of positive impact." In 2020, we were the first university to win this award twice, this time in recognition of outstanding support for the transition of female PhD and Postdoctoral Researchers into Faculty positions. We remain the only UK recipient of the award. At the same time, we learned that two of our staff (Profs Yvonne Rogers and Alexandra

Silva) were to be recognised for their contributions to gender equality in the third Suffrage Science Awards for Mathematics and Computing.

Our approach to gender diversity is comprehensive. We have structured our activities into five key areas, each of which has an Athena Swan Champion.

- ARRIVE: changing perceptions of CS in both girls and boys aged 9–18. There are many misperceptions of CS as a discipline that have currency in the minds of school pupils and their teachers and, by challenging those stereotypes, we have succeeded in breaking down barriers to entry into the academic pipeline.
- ASPIRE: showcasing CS role models and presenting diverse career paths in CS. The lack of female role models and knowledge about career options in CS often means that women do not develop dreams and aspirations to enter and stay in CS. We inspire ambitions by upholding examples of successful female staff.
- ACHIEVE: providing training and support to women in CS to realise their potential. A lack of training can be an obstacle to achieving dreams and ambitions. We provide development, training and support schemes specific to female students and staff.
- ADVANCE: increasing pathways to advancement in academic and professional careers in CS. In academia, career progression is not automatic; consequently, we have introduced structures/processes to reduce the barriers in several ways. We actively encourage applications from female staff, and ensure that promotions panels consider all staff irrespective of whether they chose to apply. The panels have set criteria and Athena Swan representation.
- AMPLIFY: We have an active programme that seeks opportunities to share best practices for gender equality, scaling up and broadening our outreach for national and international impact.

Each activity has a number of action goals, progress against which is regularly reviewed on the basis both of activities that have been undertaken and examination of objective data. Coupled with UCL-wide policies on, for example, fair recruitment, Athena Swan activities, such as encouraging applications for fellowships and creating a Proleptic Lecturer Scheme, have led to significant increase in female applicants for positions (12% in 2012, 28% in 2018). This change is reflected in appointments: neither short-listing nor appointments skewed these percentages.

The Athena Swan team have further developed departmental policies on academic staff returning from maternity or carer leave: these are now entitled to a one-term sabbatical to re-establish research, and the department supplements this with a £10,000 post-break award to help academic staff get back up to speed with their research. All new staff are required to undergo Unconscious Bias training as part of their induction programme.

Disability

Professor Cathy Holloway in UCL-CS led the creation of the Global Disability Innovation (GDI) Hub, born of the legacy of the 2012 Paralympics. This is an entirely novel cross-institutional, cross-disciplinary, academia/CIC venture that focuses on addressing disability innovation in a global context. The GDI Hub undertakes research related to disability; created a unique MSc education programme on Disability, Design and Innovation; and is responsible for a programme of work in assistive technologies that spans the globe and is supported by £20 million in DFID funding. The GDI Hub leads the disability innovation movement and is recognisable worldwide, with links to WHO, UN, and other major NGOs and governments across the world.

Creating the GDI Hub has been a key development for UCL-CS; it fuses together academic research, teaching and innovation related to disability in a highly innovative way for a CS department. In

addition to providing the leadership of the GDI hub, the activity is embedded in departmental senior management: the current HoD chairs the GDI Hub advisory committee, having been a member since its inception. Consequently, we have seen an enormous increase in the number of disabled people engaged in departmental activities (having started from a very low base), necessitating broad consideration of issues related to accessibility and the changes that need to be made to overcome structural inequality.

Wider EDI Considerations

The success of the Athena Swan and GDI Hub activities has led us to consider wider EDI aspects. While CS nationally has a significant proportion of BAME students, we have relatively few black students and, since the pipeline is crucial for academic recruitment, there are few black computer scientists in the UK. To give a stronger voice to our black staff and students, we conducted a listening campaign in summer 2020, an action led by Athena Swan committee members. We worked with Google Deepmind to establish a fellowship designed to attract black talent at the postdoctoral level. Deepmind remains strong partners in our drive to investigate and mitigate the underlying reasons behind low black representation in CS.

There are many other EDI activities within the department. The AI Centre hosts Queer in AI events as part of the annual LGBTQ History Month, with plans to host Women in AI events. Similarly, we hosted a meeting on neurodiversity with Aspirations, focussing on ways of helping companies (and the University) to value, recruit and retain autistic people.

To further embed the full breadth of EDI values in our core departmental operations and strategy, the department conceived a new EDI committee to bring together and cross-promote good practice amongst individual threads of activity, and to extend this to intersectional considerations. The committee is due to be formally established in 2021, and work has begun to define its shape and remit.

REF Selection

Our REF panel consists of the current and former HoDs, departmental manager, head of research, strategic alliances director and the dedicated REF lead, assisted by the twelve heads of groups, with 33% female representation.

Outputs were nominated by each eligible staff member and reviewed for excellence by internal domain experts. Reviews were returned to the individuals for refinement of justification statements. Two thirds of these outputs then entered a second stage where, in order to mitigate bias, the reviewers only saw the justification statements with no additional information. Second-stage reviewers were chosen for their seniority and topical breadth. Statements were randomly assigned, and each received three independent reviews. Our final selection was algorithmically created, based on a combination of review scores from both stages. Subsequent sanity-checking revealed very few instances that warranted manual intervention. Overall, this yielded an output selection that closely reflects percentage distributions of gender and ethnicity.

REF2021

Characteristic	Category	Head Count[1]	No. Outputs
Gender	Male	78.76%	78.88%
	Female	21.24%	21.12%
Ethnicity	White	79.65%	78.49%
	BAME	11.50%	11.16%
	Unknown	8.85%	10.36%
Age	Under 45	61.28%	58.96%
	45 or above	38.72%	41.04%
HESA	3	89.38%	92.43%
	2	10.62%	7.57%

Other characteristics appear generally well-balanced, too: a 1.5 percentage-point overhang of outputs for staff who did not declare a religion, 1.2 percentage points bias towards hetero-sexual authors and 1 percentage point of excess outputs for non-disabled staff.

Partitions by HESA status and, to a lesser degree, age, reveal that the more senior staff contributed disproportionately more outputs, arguably an effect of senior staff being more likely to have had further evolved research projects across the REF period.

Similarly, our impact case studies – chosen based on formal criteria – reflect our department's gender distribution (25% female; 12.5% BAME), and, owing to the long lead time from underpinning research to impact generated, are biased toward senior staff.

In terms of staff eligibility, our main concern is the overrepresentation of white research associates amongst our twelve selected HESA 2 staff: white / BAME / unknown were represented at 75% / 17% / 8%, respectively, while the overall demographic of our HESA 2 staff is 49% / 25% / 26%. Selection was based on application of the independent researcher criteria. This means that white staff are disproportionately in independent positions.

We need to better support BAME staff to promote future inclusion. Three strands of activity aim to redress this imbalance: identifying, attracting and recruiting BAME talent at all stages in the academic pipeline; nurturing individuals throughout their academic journey, building aspiration and success; and ensuring that there is equality of opportunity in seeking senior research and academic posts.

Several activities are being developed in respect of each of these individual strands. Examples include building educational links with academic institutions in Africa and elsewhere across the global

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[1] We consider head counts rather than FTE to reflect that the constraints on the number of attributed outputs are per-head, not per-FTE.

south, and open fellowship workshops to build aspirations run by the Athena Swan group. We are investing in research to understand the lack of racial diversity in the pipeline, and we are seeking to understand internal barriers through a listening campaign. In future, the department's new EDI committee will further our strategic redress of systematic underrepresentation.

## 3. Income, infrastructure and facilities

Grant proposal development support

Support for developing proposals is provided at four levels – generic, mechanism-specific, subject-specific and proposal-specific: workshops aimed at generic training in CS grant writing, largely addressing ECRs and those joining us from non-UK HEIs; regular tutorials and Q/A sessions on specific mechanisms for funding (e.g., ERC, first grant, platform, programme grants, etc.); subject-specific mentoring and review through the research groups; and regular proposal-specific reviews for each proposal itself through our internal grant review process. This internal review process simulates the real review process, with mock refereeing and interviews. Two dedicated members of the professional services team provide high-level support for financial planning and detailed administrative aspects of proposal writing. They help post-award management, freeing staff to focus on the intellectual agenda. Our departmental finance team helps staff to manage the finances of awarded grants, and the departmental HR manager oversees the process of recruiting research staff. This infrastructural support has been very successful as evidenced by our funding success over the REF period.

Income Distribution

During the reporting period, our grant income was £89.9M. The largest part (£54.4M) stems from UKRI and government grants, followed by EU-funded activities (£17.7M). Together, the two show a steady increase in funding, of 39% over the REF period; remaining sources, industry and charitable donations, quadrupled during that time frame (from annually £1.1M to £4.4M).

Our income from commercial sources, as per REF4, amounts to £6 million overall, which was more than matched by donations from charitable organisations of £6.5 million. From 2016, many of our industry sponsors shifted to an *industry donation* mechanism that is *not captured by REF4*: rising from £14k in 2013/14, to £4.4M in 2018/19 and £1.7M in 2019/20, this income totalled £6.8M.

Income Distribution
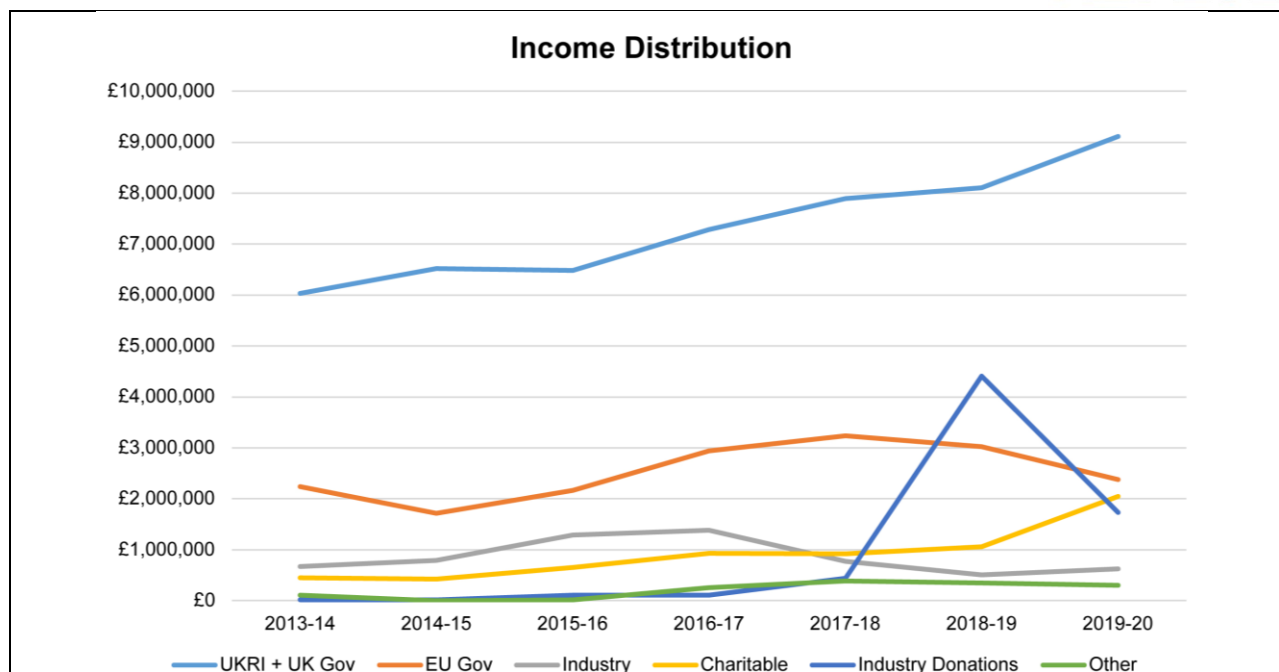
Large grants and strategic awards

We lead one EPSRC programme grant, IRIS (£6M), setting the agenda for our PPLV group, and one EPSRC platform grant (£1.5M), underpinning CMIC's translational research agenda.

We lead and participate in a wide range of consortium grants underlining our strongly collaborative identity. For example, internally, we lead the healthcare engineering and imaging (HE&I) theme of the *NIHR UCLH Biomedical Research Centre* (total NIHR award £110M, HE&I theme £4M). Nationally, we co-led (with Imperial) the **UK Interdisciplinary Collaborative Research Institute** on Cities (UCL, Imperial, Intel, Future Cities Catapult); the initial $5M investment from Intel was extended via follow-on Capstone funding ($1.5M) 2015–2018. Internationally, we participate heavily in **European consortium grants** leading H2020 consortia *EuroPOND* (total £4.1M; £1.4M to UCL), *E-DADS* (total £1.4M; £0.4M to UCL; £0.7M to UCL-CS) and *HUMANIS* (total £1.1M; £0.7M to UCL) and contributing to a further 23 EU consortia. We also lead the computing and AI stream of the *CRUK International Alliance on Cancer Early Detection* (total CRUK award ~£30M; £5M to UCL, stream £0.8M).

Our strategic focus on global challenges (Section 1) has led to major funding for the *Global Disability Innovation Hub* (GDI Hub), a research and practice centre that drives disability innovation for a fairer world, led academically by UCL-CS (Holloway) and linked with a Community Interest Company led by the former head of the London 2012 Paralympics, Victoria Austin. This unique model has attracted over £25M of research funding including a £20M initiative funded by the **Department of International Development** to develop and implement life-changing assistive technologies for people globally. The GDI Hub was a founding member of ATScale, the new Global Partnership for Assistive Technology, together with UNICEF and the WHO, and became one of the first designated WHO Collaboration Centres in January 2021 (after the REF period). We lead **two Global Challenges Research Fund (GCRF)** projects (total £2.3M) automating malaria diagnosis and developing low-field MRI techniques for childhood epilepsy in collaboration with University Hospital Ibadan, Nigeria, which led to establishment of a joint Centre of Excellence between UCL and the University of Ibadan.

Personal Fellowships

Within the REF period our staff received 9 *EPSRC Fellowships* (Alexander, Brandao, Brotherston, Livan, Murdoch, Panagiotaki, Petke, Stoyanov, Yilmaz), 4 *Royal Society University Fellowships* (Cubitt, Murdoch, Severini, Silver), 6 *ERC Grants* (*starting:* Mitra, Obrist, Silva; *consolidator*: Przulj; *advanced*: Harman, Jones), 2 *ERC Proof of Concept* (follow-ups to ERCs held at UCL: Mandayam, Mitra), 4 *MRC Fellowships* (Adams, Mourao-Miranda, Wijeratne, Young), 4 *Alan Turing Institute funded fellowships* (De Cristofaro, Danezis, Pym, Yilmaz), 2 *UKRI Future Leader Fellowships* (Oxtoby, Palombo), a *Rosetrees/Stoneygate Enterprise Fellow* (Stilli), a *Wellcome Trust Senior Research Fellowship* (Mourao-Miranda), a *Leverhulme Early Career Fellowship* (Drobnjak), a *Newton Advanced Fellowships* (De Cristofaro), 2 *Marie Skłodowska-Curie Individual Fellowships* (Mourao-Miranda, Silva), a *Royal Academy of Engineering Chair in Emerging Technologies* (Stoyanov) and a *Royal Academy of Engineering Industrial Fellowship* (Pym).

Consultancy

Consultancy is an important ingredient of our strategy for industry engagement. Over the REF period, UCL-CS has delivered consultancy for a total of £2.5M, of which £991k were generated through **UCL Consultants** (as captured by the data appendix), £51k through other divisions of UCL and £1.5M through private consulting.

Doctoral Training Centres and Programmes (DTCs / DTP)

UCL-CS has had continued success in running existing and attracting new EPSRC DTCs. CS has a leading role in the EPSRC DTCs on Financial Computing (**FC**) and Security Science (**SECReT**), and in the now ended DTCs Virtual Environments, Imaging and Visualisation (**VEIV**) (EngD) and Mathematics and Physics in the Life Sciences and Experimental Biology (**CoMPLEX**). FC and VEIV are/were led by CS, while one of the two programme directors for CoMPLEX is a member of CS, and various students were supervised or co-supervised from CS. **SECReT** is coordinated by the Department of Security and Crime Science with significant input in both lecturing and supervision from CS. During the REF period, newly acquired DTCs included the DTC on **Foundational AI** (lead: Barber), **Cyber Security** (lead: Pym) and, succeeding CMIC's Doctoral Training Programme (DTP) in Medical and Biomedical Imaging, the CDT in **Medical Imaging**, in collaboration with the department for medical physics, which in 2019 was renewed as the CDT in Intelligent, Integrated, Imaging in Healthcare (**i4Health**; lead: Zhang). The DTC on Foundational AI is housed by the UCL Centre for AI, also home to the related DTC on **AI-Enabled Healthcare** (Prof Geraint Rees, UCL Institute of Cognitive Neuroscience), which leads to fruitful collaborations between the two centres. Lastly, our staff specialised in quantum computing (Cubitt, Severini, Herbster) supervised students at the **CDT in Delivering Quantum Technologies** (Prof John Morton, Faculty of Maths & Physical Sciences), renewed in 2020, and we (co-)supervise students under the London Interdisciplinary Doctoral Programme (**LIDo**).

Technical infrastructure

We have a dedicated 10 petabytes of online storage for big data processing (50% of UCL's entire online storage), with access speeds of 100Gb/s, some of the fastest available, securely backed up. The secure data centre, accredited by the Metropolitan police, which was the first in a UK University, is being used to store UK Government classified data. In addition we have obtained accreditation to hold NIH data. Our Heterogeneous Experimental Network (HEN) was upgraded to 100Gb/s and has

a P4 configurable switch at its core. A departmental cluster of 10,000 cores is available for high performance research needs. This is continually upgraded, with an average core life of 18 months. For Machine Learning and AI, there is a GPU-based cluster with 600,000 CUDA cores. Virtual servers are available on demand, with currently 600 of these. Central support for technical infrastructure is complemented by a dedicated team of 10.7 FTE research technicians for CS, with an average of 15 years technical experience. They provide tailored research support, building enhancements for Arduinos and Raspberry Pi, designing secure IoT networks, large scale SANs and Object Stores. Our technical support team is closely involved with central UCL planning for future upgrades of data stores, clusters, security and network access speeds. They are also co-investigators, or board members, for tier-2 projects such as JADE and Dirac, consultants for secure data systems in the Alan Turing Institute, and part of the government's Exascale project, Excalibur.

We have formal collaborations with various medical faculties that provide access to world-class clinical facilities, including several 1.5T and 3T MRI scanners, the UK's first PET/MRI facility (Siemens Biograph mMR), access to two 7T MRI systems (UCL ION and KCL St Thomas'), a research-only 3T MRI based in UCL's Centre for Advanced Biomedical Imaging (CABI) enabling development of novel sequences, hardware and applications, and two 9.4T small-bore animal MRI systems (CABI and ION). We are a partner in the unique Connectom scanner in Cardiff enabling free access for development and pilot studies, and in the CRUK RadNet project developing technology to exploit the new proton therapy centre under development at UCLH. Through CABI and other research centres we have access to, and a comprehensive range of, preclinical imaging systems, including unique experimental facilities in confocal microendoscopy and photoacoustics.

Our Virtual Reality labs offer a rich selection of cutting-edge hardware in augmented reality, depth sensors, haptics and virtual reality, including a well-maintained four-sided CAVE. We have state-of-the-art motion tracking systems from OptiTrack, PhaseSpace and ART in our VR labs in Bloomsbury, and a wide-area OptiTrack system in UCL HereEast, configured to track 10×15×5m, that is also configured with photogrammetric equipment to validate measurements.

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

4.A. Industry and external bodies

While many of our research users are in academia, others encompass business, commerce and industry, government bodies, regulators, healthcare and the service and entertainment sectors. Many of them have become engaged in our core research activities, both as funders and as partners. This facilitates direct impact and provides access to resources and perspectives that further enhance our research capabilities.

Significant industrial partnerships

During the REF period, our staff collaborated with over 250 industry partners on a regular basis, developing strategic partnerships with some of the most influential deep tech companies operating in the domains associated with our leading research domains. Some examples are Google DeepMind and Facebook AI Research (in the AI domain); Adobe and Autodesk (in computer graphics and vision); Ripple and Deutsche Bank (blockchain and distributed ledgers); Microsoft and IBM (SSE); General Electrics and Elekta (medical imaging); Cisco, Arm and Nvidia (network systems and hardware platforms); Amazon Web Services and Microsoft Azure (cloud computing). These partnerships contribute significantly to the department, both with financial support and with in-kind

contributions, including access to hardware and software platforms for research and significant number of hours from their scientists and specialists devoted to working with our staff and mentoring our students.

In parallel with the above mentioned strategic partnerships, our department is also the inventor of a collaboration best practice in Higher Education in the UK, the Industry eXchange Network programme (IXN), which introduced two innovations: a teaching methodology and an engagement methodology that in the last four years have reached maturity and scale to facilitate industry projects for close to 1,000 students, from undergraduate to master level. The IXN programme includes more than 150 companies every year, from large corporations like Tesco and Bank of America to small, innovative start-ups like Hazy and Vesuvio Labs.

Spin-outs and external engagement

UCL-CS staff **founded 26 companies** since August 2013, including *Matrix Mill* (acquired by Niantic), *3DRepo* (with over £4.4M raised since founded in 2014), *Chainspace* (acquired by Facebook), *Satalia* (now with >80 employees) and *Synthace* (now 71 employees). Our staff are on the executive and/or scientific boards of many other companies, including *Synthesia* that secured Series A funding in late 2020 (Agapito, also in REF3) and *Odin Vision* (originally Odin Medical) that employs advanced computer vision in bowel cancer chirurgical procedures (Stoyanov). We have also provided consultancy to policy makers and governmental bodies, through consulting spin-outs like *Holistic AI* (Koshyiama and Kazim), closely working with the Information Commissioner's Office and the Centre for Data Ethics and Innovation.

Other examples of the vibrant innovation and entrepreneurship environment in CS are *Bloomsbury AI*, co-founded by Riedel and Bouchard (acquired by Facebook); *re:infer*, co-founded by Barber and Challis (employs 23; £3.5M VC funding); *Humanloop*, co-founded by Barber and Yilmaz (£3M VC funding); *PhaseCraft*, founded by Cubitt (employs 13 and expanding to 20; £3.7M VC funding); *KIT-AR*, co-founded by Julier and Cho (employs 10); Kokkinos is co-founder and CEO of *Ariel* (acquired by Snap, Sep 2020); Stoyanov is Chief Scientist at *Digital Surgery* (acquired by Medtronic, Feb 2020); Alexander and Parker are co-founders and directors of *Queen Square Analytics*; Parker is co-founder and CEO of *Bioxydyn*.

Also relevant is the students' innovation ecosystem that CS has created through **Conception X**, founded at UCL in 2018 by Treleaven. Today, the Conception X programme and its founders are at the forefront of innovation culture, shaping higher education, preparing academia and the next generation of PhDs for leadership roles in the economies of the future. The programme has now expanded to support students from other universities and was invited to seek funding from UKRI. 64 start-ups have been supported in the 3 cohorts launched so far, including 39 from CS students. A detailed and individual analysis of the impact and relevance of our CS students spin-outs is beyond this scope. Just as an illustration, *Rahko*, with only 7 employees, has amongst its customers several multinational pharmaceutical manufacturers and discovery CROs, and partners with AWS, IBM, Nvidia and Microsoft. Rahko continues to engage with academic staff in CS and offers MSc/PhD student internships.

4.B. Academic collaborations

For clarity, we define a collaboration to be one that led to a peer-reviewed co-authored paper and/or a funded research project in the REF period. According to this strict and measurable definition, we

have collaborations with more than 500 institutions, which include **37 of the top-50 universities** according to the 2020 QS World University Ranking, and **16 of the (other) top-20**.

UCL-CS is building a number of strategic academic relationships, defined as relationships in which there is a formal memorandum of understanding, the exchange of researchers and/or joint appointments, and physical space dedicated to the activity. At present, two such relationships are under development: the first is with **Inria, France**. This partnership started in 2018, with the appointment of Benjamin Guedj as both a tenured research scientist at Inria and as Principal Research Fellow at UCL. The initial aim was the development of a programme of activities and exchanges centred around machine learning and AI, based in UCL's AI Centre. Since then, the relationship has broadened, owing to significant overlap in academic interests between the two organisations, culminating in the formation of a larger **Inria London Programme**. (Due to COVID-19, the formal launch of the programme was repeatedly delayed, to February 2021, but the collaboration intensified already during the REF period, and despite the pandemic.)

A similar relationship is under development with **Instituto Italiano Di Tecnologica (IIT)**, driven by Massimiliano Pontil, who has long held appointments at both UCL and IIT. With an initial focus on machine learning and AI, the relationship was strengthened through the appointment of Dimitrios Kanoulas from IIT as a lecturer in robotics in UCL-CS, and there are advanced plans to establish a formal working relationship including researcher exchanges and co-supervised PhD students, both of which were delayed by the COVID pandemic.

Our department played an influential role in the development of the **Alan Turing Institute**. After our joint application with Statistical Science was accepted, we became a founding member; Prof Pym was part of the team of five founding partner University Liaison Directors that established the structures, modes of operation and initial research directions of the ATI, 2016–2018. The department has contributed a number of ATI fellows, organised events, and contributed to research programmes as well as taking key roles within UCL in managing the relationship with the ATI.

4.C. Contribution to the discipline

Funding committees

Our staff have served on panels and strategic **advisory teams for** all relevant **UK funders**, including AHRC, BBSRC, EMBL, EPSRC, ESRC, MRC Council, PAB, RAEng, UK, UKRI and Wellcome Trust, and reviewed for national fellowships and scholarships. We reviewed for **international funding agencies** of Australia, Austria, Belgium, Canada, Chile, China, Czech Republic, Denmark, EU, Finland, France, Germany, Hong Kong/China, Iceland, Ireland, Israel, Italy, Luxembourg, New Zealand, Norway, Poland, Portugal, Russia, Singapore, Sweden, Switzerland, The Netherlands and USA.

Public Policy and Expert Advice

CS staff acted as **advisors** for *House of Lords Science and Technology Select Committee* on Ageing: Science, Technology and Healthy Living, for the *UK Cabinet Office committee* on the future of You.Gov and their digital strategy, for the *House of Commons DCMS Committee*, for *NHS Choices, NICE & PHE* on evaluation of digital health technologies, and for the *Wachter Review* & *Topol Review*; **chaired** the *International Advisory Board for the Flemish Cybersecurity Initiative*; served as **witness** to the *Joint House of Lords and Commons Committee* on the Communications Data Bill, and **expert witness** for the *UK High Court* and the *US High District Court* for the Northern District of California; **served on** *Advisory Panel at the UK Information Commissioner's Office (ICO)*,

on the *Expert Advisor Group for the World Health Organization's World Report on Assistive Technology*; and last but not least, our former HoD's appointment to **Chief Scientific Adviser for National Security to HM Government**.

Notable examples include Berthouze who contributed to the All-Party Parliamentary Group on AI Evidence Meeting, 2020; Zhou who consulted on the UK Government's 'Internet Safety Strategy – green paper'; Clack has an advisory position with the Law Society's UK Jurisdiction Task Force to advise on distributed ledgers, cryptoassets and smart contracts; and Karp acted as an expert witness at the UK High Court for a case concerning data synchronisation for mobile devices.

Conference leadership

We served on **916 programme committees** (498 at first-tier venues), including all the first-tier conferences in each of the research groups' sub-areas of CS. We served on, often chaired, steering boards of *ACM CCS, ACH CHI, ACM CHI Play, ACM HotNets, ACM HotOS, ACM SIGCOMM, COMMA, ECSQARU, EG GCH, ICAT, IEEE ESEM, IEEE ICPC, IEEE VGTC, IEEE VR, LICS, Logic Mentoring Workshop, NDSS, NDSS, PETS, POPL, QIP* and *SSBSE*. Our staff have also provided **programme and area chairs** for 263 conferences and workshops (139 considered first tier) during the REF period. We **chaired conferences** that include *ACII, ACL, ACM CHI, DaLí, EGVE, EGSR, EMNLP, IMA Inverse Problems, ISMRM Diffusion Workshop, Surgeons and Engineers: A Dialogue on Surgical Simulation*; were programme chairs for notable venues, including *ACII, BMVC, EG GCH, IEEE/CVF CVPR, IPMI*; and served as area-, workshops-, tutorials- and publicity chairs for *CALCO, CVPR, CMCS, EACL, EMNLP, ICML, ISMRM* and others. On the contributing side, our staff gave more than **252 keynotes at international conferences**.

Editorial boards

Collectively, our staff hold 194 editorship positions on editorial boards, for the majority of **leading CS journals**, but also for **cross-disciplinary journals**, including *Nature Scientific Reports, PLoS One* (twice), *PLoS Computational Biology, Frontiers Digital Public Health, Frontiers Immunology, NeuroImage, IEEE Transactions on Affective Computing*. Our staff **(co-)founded the Journals** *Cybersecurity* and *Proceedings on Privacy Enhancing Technologies*; serve as Editor-in-Chief for *Inverse Problems, Cybersecurity*; as Joint Field Chief Editor for *Frontiers in Blockchain*; as Deputy Editor for *Magnetic Resonance in Medicine*; Area Editor for *Approximate Reasoning*; Launch Editor for *Frontiers in VR*; serve on the Management Committee of *BCS/BMJ Health and Care Informatics*; and curated special issues for *Approximate Reasoning, Complexity, Economic Interaction and Coordination*.

PhD examinations

We have examined **620 doctoral theses** (306 overseas).

Fellowships and honours

Our staff were awarded a *Fellow of ACM, Fellow of Royal Academy of Engineering, Fellow of Royal Society* (2x), *Fellow of the British Computer Society (FBCS), International Society for Magnetic Resonance in Medicine Fellowship* (2x *Senior*, 1x *Junior*), *Member of Academia Europaea, Allen Distinguished Investigator, Marie Curie Career Integration Grant Fellowship*, two Honorary Doctorates, from Aalto University (Finland) and Dalhousie University (Canada), respectively, and last but not least, *Commander of the Order of the British Empire (CBE)* and *UNESCO Professor of AI*.

Notable awards

ACM ISS 10-Year-Impact Award 2019, *ACM Prize in Computing*, *ACM SIGCOMM Award*, *BCS Roger Needham Award* (4x), *Eurographics Outstanding Technical Contributions Award*, *Eurographics Young Researcher Award*, *Gödel Prize*, *IEEE Harlan Mills Award*, *London Mathematical Society Whitehead Prize*, *MRC Suffrage and Science Award* (1x + 2x after the REF period), *Outstanding Service Award from the International Federation for Information Processing (IFIP)*, and many more – **47 significant awards and prizes** in total.

Best paper awards

ACM FSE, *ACM ISS*, *ACM SIGCHI* (6x), *ACM SIGSOFT* (3x), *AKBC*, *AMC Internet Measurement Conference* (3x), *CACM*, *CSCW* (2x), *CyberSafety*, *DIS*, *EARCS*, *EGSR* (2x), *ESANN*, *FSE*, *Humanoids*, *ICASSP*, *ICDP*, *ICML* (2x), *ICRA*, *ICWSM*, *IEEE ACII*, *IEEE CEC*, *IEEE ISBA*, *IEEE SCAM* (2x), *IEEE/ACM Web3D*, *INTERACT*, *ISMRM*, *ISSTA* (3x), *Journal of Network Theory in Finance Prize*, *MICCAI* (3x), *MIUA*, *Magnetic Resonance Medicine*, *Mining Software Repositories*, *NDSS* (2x), *NeurIPS*, *POPL*, *Posture and Mobility Group* (2x), *SAP*, *SSBSE*, *STAST*, *SUM*, *USENIX ATC*, *eCrime*.

4.D. Public Engagement and Outreach

Public engagement & media

Our staff give regular interviews on the BBC and for other broadcasters internationally, including Chinese National TV (Barber) and the Spanish World Service (Rogers), on topics such as AI, privacy and security, and digital health. In the written media, we contributed to publications such as The Telegraph, New Scientist, The Times, Forbes, The Register, and Wired.

Zhang received a British Science Association Media Fellowship in 2017, spending 4 weeks with the i Newspaper as a science reporter. Capra, too, was awarded this fellowship in 2018, but her host became unavailable at short notice; the opportunity fell through. Dr Livan gave invited lectures for a London-based summer school on Digital Journalism for Italian highschool students in 2019, "The research landscape on fake news".

We participate regularly in events at museums, such as the Science Museum Lates, the Science Museum Year of Engineering and the Wellcome Trust event, "In Pursuit of Pain" (2016), and at festivals including the Cheltenham Science Festival, Royal Society Summer Science Festival, Festival of Digital Health, Being Human Festival, and the Bloomsbury Festival. We regularly work with the UCL Grant Museum on joint bioinspired robotics outreach.

Minority Groups outreach

Fernandez-Reyes has led projects in Nigeria on data science for sustainable development, childhood and maternal health, and for development of awarenesses of data-driven strategies to management of malaria in endemic countries. Hailes has co-directed a number of IoT workshops aimed at students from Africa (co-funded by UNESCO/UNECA) and has run multiple outreach sessions in the Caribbean focused around robotics and wireless sensing.

We encourage school-age internships and A-level student mentoring schemes, such as the Windsor Fellowship mentoring programme, run jointly by Windsor Trust and Royal Society, aimed at supporting and encouraging BME A-level students considering careers in STEM.

Parkin has led a project "Gender and IoT" that led to several workshops, training events and an article in a practitioner magazine ("'Internet of Things': How Abuse is Getting Smarter", in *Safe – The Domestic Abuse Quarterly*, 2019).

Schools outreach

CS has a long history of creating and leading schools outreach programmes, both alone, with others in the Faculty and with external partners, most notably the In2Science charity. To facilitate this, we have built strong links with local schools (e.g., all secondary schools in Camden and some around Stratford in East London), helping to educate children and provide CPD for teachers in our local area, as well as opening our doors to those from other areas of the country. Naturally, we have worked with CAS and co-led the local hub, and we are members of the Institute of Coding. As well as work in the classroom, we have created, supported and run a number of summer schools for school children, as well as significant events for Ada Lovelace day and the Big Bang fair for STEM. Our activities even gained international reach – Hailes advised the UAE government on school education, on location, and we have worked with the government of St Lucia and with Gibraltar on schools' computing education, as well as with teachers from a variety of other countries – we hold an annual event with teachers from Norway, for example.

To support our teaching activities, our researchers created two hardware platforms: the Engduino, as part of the India-UK Advanced Technology Centre phase 2 award, and the MagicCube. More than 1000 Engduino devices were created and distributed in both the UK and overseas. The MagicCube research project (Marquardt, Rogers) worked with over 9 primary and secondary schools in the state-funded, independent, mainstream and special-education categories, across London and the South of England to deliver IoT and programming classes to students in line with the national curriculum, including a Science Museum Year of Engineering workshop, an EU Codeweek introductory tinkering and programming session, Digital Celebration at Emirates Stadium, MozFest 2016 and 2017, Grenfell Tower Kids Summer Coding Camp and a Royal Institution Masterclass on Engineers Save Lives.

We have also led activities for nursery children such as the Nursery Science pilot project (Cubitt, with Amanda McCrory, Lecturer in Early Years Science Education, Institute of Education) designing and running science activities for 2–4 year-olds, and the Early-Years Science project, a full-scale 2-year pilot project, funded by a £10,000 Royal Society public engagement grant, designing and running science activities for 2–5 year-olds, and producing accompanying materials (worksheets, videos) aimed at parents and teachers, made freely available online.