Institution: University of Bristol
Unit of Assessment: 11: Computer Science and Informatics
1. Unit context and structure, research and impact strategy

Context and structure

Computer Science and Informatics (CS&I) is a key area of research within the School of Computer Science, Electrical and Electronic Engineering, and Engineering Mathematics (SCEEM), in the Faculty of Engineering. It encompasses a thriving research community of internationally-recognised scholars who are making significant contributions to industrial and societal challenges. Since REF2014, the digitalisation of all areas of life has continued to accelerate and over this REF period, we have made many important contributions to the building of a new digital world. The breadth and quality of our research, our training provision and our partnerships ensure our work has meaning and impact.

There have been significant internal and external investments in SCEEM during this REF period, with £26m investment from the University of Bristol (UoB) supplemented by major investments from funders and industry. The result is that we are submitting 59.15 FTE staff (41.6 FTE in REF2014, >90% of the staff body) who lead a research community of 62 PDRAs and 129 PGRs.

We offer colleagues access to internationally-leading research facilities and infrastructure, and provide colleagues at all career stages with a vibrant, supportive and collegial research environment. Being embedded in a highly integrated Faculty of Engineering has supported particularly rich and diverse internal and external interactions and collaborations, a highly co-creative approach to research, and strong commitment to engaging with research users in diverse ways. We also have comprehensive support for all aspects of research from UoB's Research and Enterprise Development Division (RED, see Institutional Environment Statement (REF5a)) and, at Faculty-level, from the Faculty's Industrial Liaison Office (ILO) which enables us to make significant contributions to end-users at scale. Our research aspirations are further supported by a dedicated Faculty team of 67.4 FTE technical professionals and 44 research support staff.

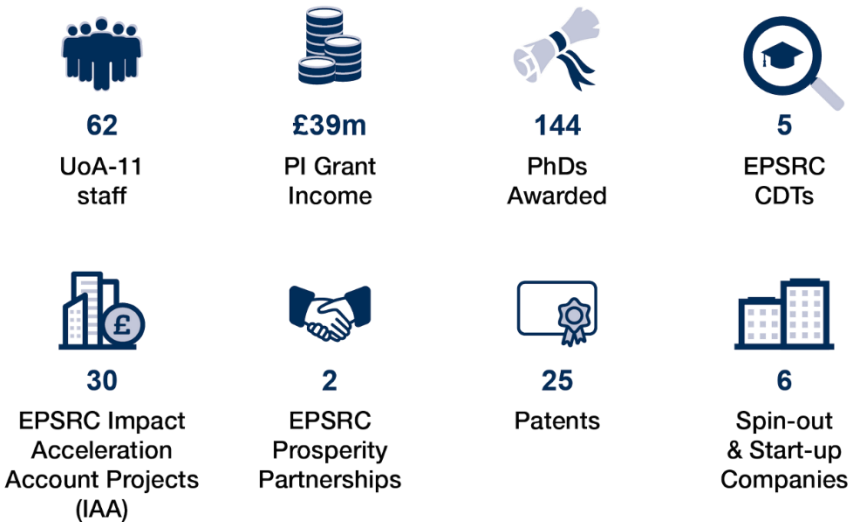

Figure 1: Overview of UoA11 over the REF period.

Research Achievements

This REF period saw substantial income growth, exceptional CDT success, development of stronger and deeper industry links, significant external impact, and a large number of competitive fellowships secured.

In REF 2014, the UoA11 research strategy was: “attract the best staff and students; target strategic collaboration with industry and to collaborate with the best researchers nationally and internationally”. This section sets out our achievements against these goals.

Total UoA11 submissible research income for 2013-2020 was £39m, representing a 146% increase over REF 2014 (£15.8m). Research income was £131k per staff p.a. compared to £76k in REF 2014, a 72% increase. Funding highlights include:

- The Isambard GW4 Tier 2 HPC Centre for Advanced Architectures (£7.1m [Isambard 1] 2016-2021 and [Isambard 2] 2020-2023, McIntosh-Smith)
- EPSRC Platform Grant in Vision Science (£1.2m, Bull)
- Three European Research Council (ERC) Advanced Grants (Cristianini, Oswald, Smart)
- Recent major awards, including
    - MyWorld Strength in Places programme for the Creative Sector (£46m, with £30m from UKRI, Bull)
    - Bristol Digital Futures Institute (BDFI) (£100m, with £29m from Research England), led by UoA12 and Social Sciences, but with significant input from UoA11.

We have supported UoA11 staff in securing 18 highly-competitive individual fellowships, including (ECRs in **bold**):

- Seven EPSRC Fellowships (Chitchyan, Clifford, Damen, Fraser, **Metatla**, **O’Kane**, Smart)
- Leverhulme Research Fellowship (Achim)
- Leverhulme Leadership Award (Lepora)
- Two Leverhulme Early Career Fellowships (**Roudaut**, **Katsenou**)
- Royal Society University Research Fellowship (**David**)
- Royal Society Industrial Fellowship (Nunez-Yanez)
- RAEng Senior Research Fellowship (Pamunuwa)
- Two Royal Society Advanced Newton Research Fellowships (Carranza, Mayol-Cuevas)
- Marie Curie Rise Scheme Fellowship (Smart)
- Marie Curie Experienced Research Fellowship (**Katsenou**)

Exceptional success in the 2019 EPSRC call for Centres for Doctoral Training (CDTs) reflects our track record in providing excellent training in a supportive environment (as evidenced by two EPSRC CDTs awarded in 2013: in Communications and Robotics). Among six new CDTs across the Faculty of Engineering, those directly related to UoA11 (Director or Co-Director) are:

- Trust, Identity, Privacy and Security in Large-scale Infrastructures (£6.2m, 2019-2027)
- Interactive Artificial Intelligence (£6.8m, 2019-2027)
- FARSCOPE-TU CDT in Future Autonomous Robotic Systems (£4.8m, 2019-2028)
- Digital Health and Care (£6.3m, 2019-2027).

We also co-host a Wellcome Trust PhD Programme in Neural Dynamics (£1.9m, 2016-2023).

Thales and Liverpool Victoria General Insurance (LV=GI) have both located technical teams within the Faculty to benefit from academic expertise and to facilitate collaboration. Bristol is home to one of just seven ARM Centres of Excellence and UoA11 leads or participates in two EPSRC Prosperity Partnerships involving multi-national companies (Thales and Rolls-Royce).

There was significant internal and external investment during the period. UoB committed c. £23.5m from its Estates Strategy and a further £2.5m for equipment, augmented by >£7m in capital investment from EPSRC in high-performance computing. From 2023, UoB's Temple Quarter Enterprise Campus (TQEC, see REF5a) will be home to new facilities to support research in digital technology led by UoA11 (AI, Cybersecurity, Vision, and Interaction).

The Faculty's EDI strategy produced an increase in female staff (17.7% of UoA11 staff, 9.5% in 2014), including three professors in UoA11 (none in 2014). Our international staff (40%) come from 18 countries. Table 4 (page 24) shows that 98.4% of the submitted REF outputs involve collaboration, and our global reach is demonstrated by the fact that 48% of the outputs have an international collaborator.

Research Strategy

In early 2016, under UoB's Vision and Strategy, the Faculty of Engineering developed an ambitious growth strategy to make a perpetual, positive impact in the world. This was refreshed in 2020 under a renewed Faculty leadership team. The underpinning priorities are to:

- apply world-leading research to grand societal challenges
- inspire and develop future leaders through a challenging educational offering
- partner with local and global innovators to accelerate impact
- advance equity and diversity

To achieve our ambitions, our future research objectives for 2020 and beyond are to:

- demonstrate academic leadership of the highest calibre and develop future leaders
- continue to grow our research reputation
- recruit, retain and invest in our great staff and students
- enhance stewardship of our key research partnerships
- increase and diversify our external research funding
- celebrate diversity within our community and encourage inclusivity in all we do

Research Structure

Our research groups encourage inter-generational idea sharing, mentoring and training, from PGR through postdoc and early-career academic to professorial level. A critical mass of expertise in each discipline also supports collaboration between the five research groups in UoA11, with many staff belonging to more than one research group and hence contribute to both discipline-based and inter-disciplinary research:

Artificial Intelligence and Autonomy (AI&A)

AI&A has 21 academics, 28 research associates, and 50 PGR students. It is led by Liu, who is a member of the EPSRC ICT Strategic Advisory Team (ICT SAT). It was supported by 70 grants and income of £8.9m.

AI&A works across four domains, each led by a champion: **Machine Learning** (Flach), **Robotics and Autonomy** (Lepora), **Neural Computation** (Houghton) and **Financial Data Analytics** (Cliff). Machine Learning's strength in putting "humans in the loop" in artificial intelligence systems led to the award of the Interactive Artificial Intelligence CDT. Robotics and Autonomy anticipates a future which integrates traditional robot control with modern machine learning and insights from nature. Neural Computation seeks insights into computation and mathematics by studying how the brain works, and Financial Data Analytics is concerned with the application of machine learning in the financial sector and its relationship with the sector's legal and regulatory framework.

The group is well-connected to the Alan Turing Institute, UoB's JGI, the Bristol Robotics Laboratory (BRL) and international academic networks. AI&A has more than 30 external partners including Facebook, Google, Microsoft, FiveAI, Amazon, EDF Energy and Dyson, and make significant contributions to several important cross-disciplinary grants including the large-scale digital health project SPHERE (Flach, Santos-Rodriguez; £15.2m).

Cybersecurity and Cryptography (C&C)

C&C has nine academics, 12 research associates, and 22 PGR students. Leadership is provided by Rashid, who chairs the Scientific Advisory Board of EPSRC-NCSC Research Institute on Sociotechnical Cyber Security (RISCS) and served on two UK government cyber expert groups. It was supported by 54 grants and income of £9.8m.

The **Cybersecurity** domain (champion: Rashid), formed in January 2018, leads on security and vulnerability analysis of cyber-physical systems, including the development of novel countermeasures (e.g. intrusion detection systems, vulnerability analysis tools, novel security architectures, and human and organisational factors) along with data science approaches to cybercriminal activities and countermeasures.

Research in the **Cryptography** domain (champion: Page), established in 2000 by Prof. Smart, is focused on the hardware and software needed to implement secure systems and spans a broad range of theoretical and practical aspects, from foundational research and number theory to design and formal security analysis of cryptographic protocols. Current specialisms include high-assurance design and implementation techniques, implementation attacks, and post-quantum cryptography.

Strong combined research capabilities have made UoB a major centre for cybersecurity and cryptography research from the mathematical to the practical. Rashid leads the National Cyber Security Programme, the Cyber Security Body of Knowledge (CyBOK) project, which has defined foundations for the field and underpins national certification of academic degrees by the National Cyber Security Centre (NCSC). The group leads projects as part of major national programmes (RISCS, RITICS, RISE, PETRAS, Discribe), hosts a CDT in Cyber Security, and plays an important role in the RF Open Attack Surface as part of the £2.23m SWAN prosperity partnership. Key collaborators include NCSC, Vodafone, Google, HP, Airbus and Thales. The group also has close relationships with the Heilbronn Institute for Mathematical Research.

Visual Information Laboratory (VI-Lab)

VI-Lab has 10 academics, 14 research associates, and 28 PGR students. It is led by Bull who is a Fellow of both the IEEE and IET, and PI of a Platform Grant in Vision Science (Vision for the Future, 2014-2019). It was supported by 65 grants with income of £7.7m.

VI-Lab's international reputation is built on fundamental and applied interdisciplinary research encompassing computer vision, image processing and visual communications. VI-Lab is a key element of the Bristol Vision Institute (BVI, of which Bull is founder and Director), an interdisciplinary organisation of 160 associates which promotes research collaboration in vision science and its applications, across computer science, engineering, biology, psychology, medicine, and the creative arts.

In egocentric vision, Damen led the collection and release of EPIC-KITCHENS, the world's most comprehensive dataset for in-home health monitoring and activity analysis. Consequently, Damen was one of only 20 academics worldwide to be named a Nokia Research Collaborator in 2016, as well as a Facebook Research Collaborator in 2019. Other highlights are Burghardt's animal biometric method, deployed by Save Our Seas Foundation to track and identify great white sharks, and research expertise in computer vision, utilised by Amazon, Samsung, Perceptual Robotics (Mayol-Cuevas, Calway) and others.

Research excellence and longstanding collaborations with the creative sector in the South-West have culminated in the ISCF/AHRC Bristol and Bath Creative Industry Cluster and leadership of the £46m MyWorld project, whereby UoA11 researchers connect regional and national creative partners (e.g. the BBC, Aardman Animations, Bristol Old Vic) with global tech giants (Netflix, Google, Microsoft), to forge new creative sector opportunities in the South West.

Fundamentals of Computing (FoC)

FoC comprises 14 academics, 14 research associates, and 19 PGR students, led by McIntosh-Smith, who is Technical Chair of the £50m UKRI ARCHER2 national HPC service design and procurement project and sits on the EPSRC's e-infrastructure strategic advisory team as well as the EPSRC resource allocation panel for the UK's national supercomputer resource. The group is supported by 61 grants with an income of £7.6m and a further £7.1m of EPSRC capital grants.

The group works across four domains of interest, each led by a champion. **High-Performance Computing** (McIntosh-Smith) focuses on the application of heterogeneous and many-core computing to solve large-scale scientific problems with a focus on energy-efficient adaptive computing for scientific, video and machine learning applications. **Algorithms and Complexity** (Clifford) aims to provide scalable solutions to existing problems and to understand the limits of what is possible. **Programming Languages** (Wang) spans theoretical foundations, language design and implementation, program analysis and synthesis and works with both agile start-ups, like DiffBlue and industry giants, like GitHub, whose code navigation features are powered by our work on algebraic effects (see impact case study on GitHub). **Trustworthy Systems** (Eder) focusses on all aspects of trustworthiness throughout the system stack, from hardware to software, (e.g. safety and functional correctness, predictability, security, privacy), as well as traditional dependability (integrity, robustness, reliability and graceful degradation).

By uniting these domains, the group provides a multi-faceted understanding of key issues like reliability, scalability, and reusability. The group co-leads (with AI&A) the £3m functionality node under the UKRI Trustworthy Autonomous Systems Call and Pamunuwa was awarded an RAEng Senior Research Fellowship with Microsemi. Industry partners include Cray, Arm, the Met Office, Huawei, Intel/Altera, NVIDIA, Fujitsu, XMOS, Graphcore, XILINX, AWE, and Rolls-Royce.

Bristol Interaction Group (BIG)

BIG has eight academics, 10 research associates, and 10 PGR students, and is led by Roudaut. The group is supported by 32 grants and £5m research income.

The group's research includes novel interactive devices, and their deployment and evaluation in everyday settings such as healthcare, sustainability and fabrication, including the recent development of artificial skin. The relationship between technology and everyday life "in the wild" is evolving to inform health, care and wellbeing projects (diabetes, multiple sclerosis, mental health, hearing loss and older-adult care). The HCI group works with industry partners such as Quin and PassiveSystems, grassroots activists such as WeAreNotWaiting and Hearing Hacks, public bodies such as Bristol City Council and the BBC, and charities such as Knowle West Media Centre.

BIG is proud to be a very inclusive team: 14 researchers and eight of the academics are female and many balance successful careers with family commitments. Major successes during the REF period include:

- EPSRC Leadership Fellowship (Fraser)
- £1m EPSRC grant on Virtual Realities (Cater)
- EPSRC Fellowship (Metatla)
- EPSRC Environment Change Challenge Fellowship (Chitchyan)

Funding was obtained from XMOS, Texas instruments, Royal Society, Microsoft Research, AHRC, Ultraleap, Leverhulme Trust, Nvidia and EC. The group set up strong interactions with industrial partners such as Nokia, Microsoft Research, Tactual Labs, Kooth, and Quin.

Impact Strategy

We want all our researchers to maximise the impact of their research. Support and training are coordinated by the School Impact Director, who sits on the School Management Team. The Impact Director helps academics and research groups recognise and facilitate the wider impact of their work. He also works closely with the ILO and RED teams (see REF5a) to prepare Innovate UK, EPSRC IAA and ISCF proposals and advise on the management of IP and the setting up of spin-out and start-up companies.

We are continually developing ways to:

- encourage and support diverse impact activities which build on academic research success: e.g. industrial secondments and co-funded posts.
- develop meaningful relationships with end-users for effective collaboration and technology transfer, thus maximising the benefit of our research to society, e.g. partnership with LV=GI.
- recognise and reward those who actively engage with impact activities (up to two of ten promotion criteria relate to engagement and impact).

We have made significant progress in creating impact through:

- Judicious use of the EPSRC Impact Acceleration Account. Over the REF period, UoA11 secured 30 IAA projects (value £840k) to support commercialisation, knowledge transfer secondments, and early-career researcher kick-starter grants. This underpinned two of the impact case studies: Ultraleap and XMOS. The IAA also supported the appointment of a

Business Fellow (McIntosh-Smith) to lead industry-facing activities that showcase and promote research impact.
- Supporting staff to secure intellectual property through patents where appropriate: e.g. Pamunuwa's work with Microsemi.
- Two new External Advisory Boards for the Department of Computer Science (one with a specific focus on data science) to complement the long-standing Industrial Advisory Board in the Department of Engineering Maths. These are regularly consulted on research strategy.
- Impact workshops and training events for academics and postgraduate students.
- Funding for summer undergraduate internships focussed on impact.
- Embedding impact training in our CDTs and ensuring that industrial partners provide opportunities for collaborative projects.
- Establishing new companies such as Unbound Tech, Mogrify, and Perceptual Robotics and continuing to support our more-established spin-out companies; Ultrahaptics (now Ultraleap) and XMOS (both impact case studies), which have seen continued success and growth (e.g. XMOS itself spun out a successful new company called Graphcore, which to date has raised $710m in investment and is valued at $2.8B).
- Strengthening existing partnerships through EPSRC Prosperity Partnerships (Thales, Rolls-Royce) and embedding industrial partners in UoA11 (Thales, LV=GI).
- Visiting industrial fellows, hosting industry on campus, and secondments of academic staff to commercial organisations (see Section 2).

Impact Example: In 2017 global technology company Thales Group chose the University of Bristol (UoB) as its first UK strategic partner university. Thales has worked with UoB for 20 years on several joint UK/EU-based research projects, while supporting over 15 doctoral students. Thales' programme (security, communications, sensors, autonomy and complex systems), focusses on the Faculty of Engineering.

> *"Thales has a real capacity to innovate through collaboration across the entire high-tech ecosystem, including with start-ups and universities. We are proud to broaden our partnerships by working with the University of Bristol, which has excellent research facilities and high-quality students looking at complex technical challenges."* ***Marko Erman, Thales Chief Technical Officer***

PolicyBristol facilitates engagement with local councils and central government (see REF5a). Several academics have served as consultants or advisors to major UK and EU governmental departments and regulatory bodies (see Section 4) and have been called to serve as senior expert witnesses in major civil and criminal legal cases (Cartlidge, Cliff, May).

The research of Preist and Schien makes it possible to assess the energy (and climate change) impacts of digital services across the internet. Guardian News and Media used their research to enhance their Corporate Social Responsibility Policy, adopting a new environmental KPI. The BBC used it to change practice in both R&D and board-level strategy, by assessing change in UK electricity demand induced by different strategies for the broadcast-to-streaming switchover.

Interdisciplinary Research

We work within and across research groups, across Faculties, with other institutions and organisations both nationally and internationally to maximise our success, recognising that collegiality, collaboration, and partnership are at the heart of impactful research.

In line with UoB strategy to foster interdisciplinary research (see REF5a) we strongly encourage researchers to explore collaborations outside their research groups through engagement with:

- cross-Faculty research centres (e.g. BVI, Bristol Neuroscience (BN))
- University Research Institutes (Jean Golding Institute (JGI), BDFI, and Elizabeth Blackwell Institute (EBI))
- inter-University partnerships (e.g. GW4 and BRL with UWE)
- third-party organisations (e.g. Bristol VR Lab in collaboration with UWE, Bath Spa University, Rocketmakers - funded by Innovate UK and the West of England Combined Authority)
- international links (e.g. Smart at KU Leuven (Belgium), Mayol-Cuevas at Amazon (USA), Warinschi at Dfinity (Switzerland)).

Not only does this facilitate innovative research ideas but exposure to interdisciplinary, intersectoral and international research experiences has been shown to positively influence research integrity.

To support such interdisciplinary work, the RED team works with the SCEEM Research Committee, tracking available sources of research funding to support interdisciplinary research, and proactively encouraging individual researchers to apply for specific funding calls as they arise.

Working across Faculties: VI-Lab, AI&A and C&C have been active participants in BDFI (see Section 2 of REF5a). The AI&A group is closely involved with the JGI. CNS works in collaboration with BN, while BIG uses participatory design to work with medics and patients to create innovative therapies.

Working across universities: UoB is part of the GW4 alliance, along with Bath, Cardiff and Exeter, and this provides a framework for collaboration in order to strengthen the economy across the region through undertaking pioneering research with industry partners.

Example: The GW4/Met Office/Cray Inc. Isambard computer is the world's first ARM-based production supercomputer, and as the Isambard impact case study demonstrates, provided the template for a new generation of ARM-based supercomputers, creating a new market worth hundreds of millions of dollars.

Working with other organisations: In recognition of our research strength in data science and strategic desire to grow these activities, UoB joined the Alan Turing Institute in 2018. Five academics in UoA11 are Turing Fellows (Flach, Houghton, McIntosh-Smith, Palomares Carrascosa, Rashid) and have engaged in the Ethics Advisory Board and in grant-funded projects. In 2020, Bristol was chosen as one of two centres for the Enrichment Scheme and will welcome 15 PhD students in October 2021. Flach's Turing Fellowship was supported by a two-year grant entitled "Towards a Measurement Theory for Data Science and AI": the project resulted in two

conference papers, an invited journal submission, a tutorial, and open-source software. The work attracted international attention, leading to five invited talks and several seminars.

Open Research

As detailed in the REF5a, UoB and UoA11 are committed to open access to research. Pre-final-print copies of publications are routinely placed as open access on our institutional document servers, arXiv and bioRxiv, following the requirements of major funding agencies. Our research data is accessible via UoB's Research Data Storage Facility, which provides secure, long-term data storage systems. Where computational code is a key deliverable, researchers are encouraged to make the source-code written as research tools freely available via public-domain open-source repositories such as GitHub, thereby enabling peer scrutiny, replication, and extension of our work. A key code navigation tool in GitHub was re-implemented based on research in UoA11 (see GitHub impact case study).

Research Integrity

UoB is committed to meeting the commitments of the Concordat to support Research Integrity and is a member of UKRN, a network of over 40 UK institutions that works with researchers, universities, and a range of stakeholders to promote initiatives that further research rigour, robustness and quality. Furthermore, UoB is a signatory to the Declaration on Research Assessment (DORA - see REF5a).

As CS&I research increasingly relies on data and/or considers how humans interact with technology, our researchers adhere to special procedures for working with and collecting data from living participants. We require ethical working to be embedded, from the planning stage to write-up and publication. We emphasise through training and open dialogue that students and staff are expected to undertake research in an ethical manner. The Faculty Ethics Committee (chaired by Houghton) upholds robust values around responsible innovation, ensuring that research projects are conducted professionally and ethically through a constructive, supportive and facilitative dialogue with researchers.

2. People

Overview

It is our ambition to shape the digital world by ensuring that our staff and PGR students reach their fullest potential as computer scientists and engineers. We seek to recruit from the widest possible pool of candidates, to encourage creativity, and to create a supportive, inclusive community in which all colleagues can flourish. We are mindful of the importance of maintaining a balance between senior academics and early-career researchers to maximise the scope for active collaboration and mentoring, and to ensure succession planning through training and development.

We are submitting 21 professors (three female), 25 readers/senior lecturers/associate professors (five female), 15 lecturers (two female), one senior research fellow (female). We acknowledge a historic lack of diversity and have been striving to improve equity and inclusion so everyone can excel. Over the last six years, our approach has developed, and we are determined to ensure that the composition of our academic body and the culture and environment of SCEEM better reflect

wider society. We take pride in having a culture of opportunity where all staff and all PGR students can flourish.

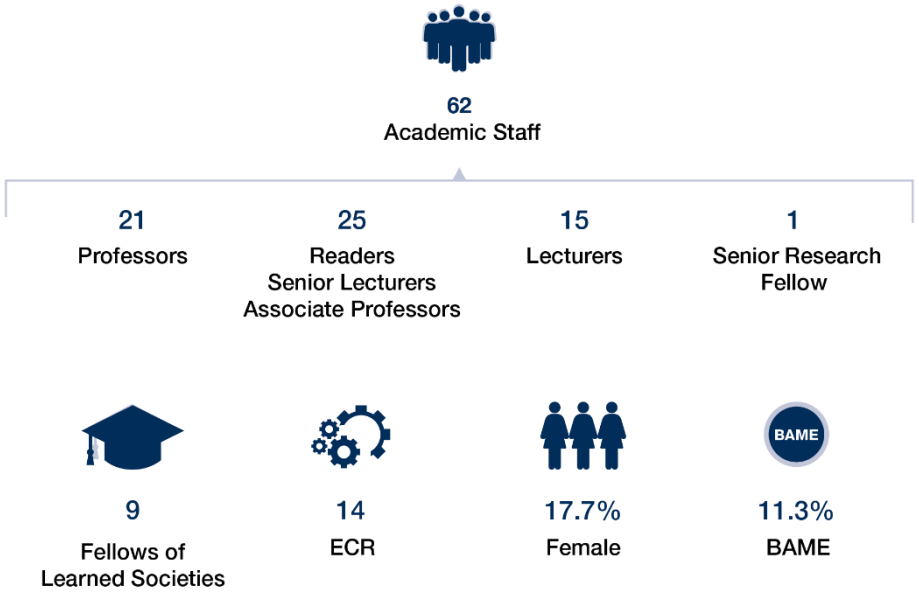

Figure 2: UoA11 REF staff submission.

Staffing strategy and staff development

It is our ambition to shape the digital world by supporting our staff and students to reach their fullest potential as computer scientists and engineers. We recruit from the widest possible pool of candidates, encourage a desire to be creative and enable a truly diverse and inclusive community to realise its vision. A balance between senior academics and early-career researchers maximises scope for active collaboration and mentoring and creates a pathway for succession-planning through training and development.

A national skills shortage in computer science and engineering, strong demand from top-quality students and our sustained track record of research excellence resulted in UoB's strategic decision to grow the Faculty. Since the last REF period, Faculty academic staff numbers (including research staff) have grown from 399 in July 2013 to 481 in July 2020 and our UoA11-returnable headcount grew by 48%, from 42 to 62. During the REF period UoA11 had a healthy turnover. Eleven pathway one academics, three professors (2.5 FTE), five senior lecturers/readers (4.5 FTE), and three lecturers left, while four professors, 11 senior lecturers/associate professors (10.2 FTE) and 14 lecturers were recruited. The good record of promotion to professor (mirrored at more junior levels) is evidence for the success of our staff development.

Notable high-level appointments (4 **female**):

- strategic appointment: 2018 Rashid
- senior appointments: 2015 Bullock, 2017 **Liu**, Nabney
- promotions at professorial level: 2016 **Eder**, Mayol-Cuevas, McIntosh-Smith, **Oswald** (left 2019), 2017 Preist, 2018 Achim, Calway, **Cater**, Lepora.

Strong early-career appointments with outstanding research potential (4 **female**):

- 2015 **Katsenou**, O'Donnell, Santos-Rodriguez
- 2017 Cartlidge, **Chitchyan**, **O'Kane**, Ramsay
- 2018 Bird, Konrad, Costa, Marshall, Pasquier, Wang
- 2019 Aitchison, Dupressoir, Edwards, Lapinskas, **Martindale**, McConville, Rawat
- 2020 Craggs, **David**, Kavvos, Metatla, Simpson.

As an example of effective recruitment, we extended our expertise in cryptography into the domain of cybersecurity. Rashid was a strategic appointment from Lancaster in January 2018. His leadership in C&C resulted in five new computer science academic posts aligned with cybersecurity under UoB's strategic investment programme.

We successfully employed "proleptic" appointments to retain talented staff in a permanent academic post upon completing a substantial competitive research fellowship (for example, Chitchyan, EPSRC Environment Change Challenge Fellowship).

Over the REF period, the following improvements to recruitment and selection procedures have helped increase diversity:

- all advertisements stated that part-time and job-share applications will be considered and link to our family and career network
- gender-diverse interview panels
- mandatory training for all panel members in EDI including avoiding unconscious bias
- an EDI-related question was asked of interview candidates
- separate male/female shortlists piloted

Our future staffing strategy is to invest further in growing our staff complement: early-career academics to match the growth in education and research activities, and strategic appointments to deliver large-scale research projects (such as BDFI and MyWorld) and to develop other research strengths of the Faculty (for example, to support Digital Engineering and Sustainability).

Career progression and promotions

We strongly encourage staff to use the annual review process to discuss research objectives, obtain feedback on performance, identify development and training needs, and receive guidance on promotion. Individuals benefit from a wide range of internal courses and bespoke training, including proposal mock-panel interviews. Those in management roles are supported to undertake appropriate development programmes.

Advice on promotions is provided through line managers and diversity in applications is encouraged through mentoring and CV-sharing. The Dean and HR lead an annual 'demystifying promotions' workshop to explain the process, so staff (particularly those from under-represented groups) have confidence to apply.

Staff support

We recognise the pressures and challenges associated with pursuing an academic career. The following Faculty activities and schemes, implemented during the REF period, support our academics in their research:

- Our workload model ensures a fair and transparent balance between teaching/administrative responsibilities and research.
- A protected afternoon each week is used to ringfence dedicated research time.
- Our timetabling constraints process offers all staff teaching duties scheduled around caring responsibilities.
- Line managers are encouraged to focus on a quality induction, with monthly School and Faculty induction sessions. An online repository of materials is available to new starters (with particular focus on ECRs).
- Clear documentation is provided on what is expected from academics in terms of research, education, PGR supervision, administrative and citizen duties and what support they can expect.

In response to staff survey feedback in November 2019, Faculty Board approved a Study Leave Policy for implementation from September 2021 (delayed by Covid-19). Eligibility criteria relate to the individual's prior contributions to teaching, research and admin/citizenship. We will consider how study leave fits with the individual's own development/ambitions/career plans and with broader research group/School/Faculty strategy/objectives. We are confident that study leave will enhance the research environment and quality of research outputs by allowing academics to focus on more ambitious projects. Periods of study leave to undertake research at other HEIs, in the UK, overseas or in industry, have been supported previously but a formal scheme will encourage staff to be more ambitious in their applications.

Several staff have been supported so they can engage with both commercial and academic institutions in flexible ways that suit them and the partner, including:

- partial secondments, (Mayol-Cuevas at Amazon, Warinschi at Dfinity)
- partial buy-out (Martin, Senior Fellowship at BT)
- visiting international positions (Achim, Université de la Cote d'Azur).

Support for early-career researchers (ECRs)

Of our UoA11 staff, 23.6% are ECRs. In their first two years, they are given a reduced workload (usually half), priority for PGR studentships, a mentor and personal start-up funding to pump-prime new activities and support attending conferences and developing industrial links. In addition to the UoB-level ECR career-development activities (e.g. grant-writing, leading research teams, and public engagement through Bristol Clear), the Faculty's tailored ECR development framework offers training and networking activities, monthly meet-to-talk coffee sessions, research sandpits, individual mentoring and researcher group-mentoring. ECR-focused activities are coordinated by (later-stage) ECRs and supported by senior academics. For example, in the Faculty's annual pump-priming call, over 70% of the projects funded have ECRs as co-applicants.

UoA11 has 62 postdoctoral research associates (PDRAs). As noted in the REF5a, we are committed to the Concordat to Support the Career Development of Researchers. Staff are aware of the responsibilities for managers and the organisation in terms of recruitment and selection, recognition and value, support and career development and diversity and equality.

The Faculty's dedicated project manager for staff experience works with colleagues to deliver actions identified from the 2015 staff survey with a particular focus on PDRAs. We give our researchers a voice to raise concerns and shape their own experience. Through a network led by

the PDRAs themselves, they can meet colleagues across the Faculty, benefit from lateral/peer mentoring and learn about the many UoB support functions. PDRA representatives (elected by the PDRAs) sit on the SCEEM Research Committee and feed into decisions about research strategy and targeted training.

We have recognised that the precarious nature of fixed-term contracts generates stress for research staff and prevents them feeling truly included and valued as members of the community. We have moved away from fixed-term contracts towards open-ended contracts with fixed term funding. PDRAs are most at risk from uncertain funding and we are increasing efforts to provide them with opportunities to build skills and experience to enhance their employability, whether they remain in academia or move elsewhere (with both career choices encouraged as equally valid). Initiatives include student supervision, teaching, and running their own research projects (e.g. summer internships).

Our early career pipeline: Our research strength and environment ensure that we are an attractive location for new early-career staff bringing independent fellowships to Bristol. During the REF period, UoA11 hosted 6 independently-funded Fellowships held by ECRs (see page 2).

Support mechanisms, training and supervision of PGR students

Our PGR student body grew from 70 in 2013/4 to 129 in 2019/20. We fully integrate PGR students into our rich research culture. They have world-class opportunities to support their development as leaders of future research, innovation and impact. Our supportive environment nurtures and develops deep technical expertise, creative problem-solving skills, technical and non-technical communication, and training in enterprise, innovation, and technology translation.

UoA-11 PGR community:	Female	Industry funded	International Students
2019 - 2020	**26% ↑**	**5.4% ↑**	**30% ↑**
2013 - 2014	18%	2.7%	25%

Figure 3: Growth of the UoA11 PGR community.

A small selection of examples of PGR student successes as follows:

- Ellie Birbeck - best student paper, IEEE SSCI 2018
- Tom Deakin - best paper, CUG 2019; serves on Khronos international standards body for SYCL parallel programming language; proceedings chair for IOWCL workshop for three years
- Patrick Atkinson - language committee for OpenMP Architecture Review Board (2018)
- Kacper Sokol - won funding from Thales in 2018 to develop fairness, accountability and transparency forensics toolbox
- Hazel Doughty - co-organised Women in Computer Vision at CVPR 2020

Funding

The Faculty's track record of excellent postgraduate training resulted in exceptional success in both the 2013 and the 2019 EPSRC calls for Centres for Doctoral Training. Bristol was the most successful institution in the 2019 call, and the Faculty leads six centres and participates in a further two.

In UoA11, we lead two new CDTs:

- CDT in Interactive Artificial Intelligence (£6.84m, 2019-2027) (PI: Flach)
- CDT in Trust, Identity, Privacy and Security in Large-Scale Infrastructures (TIPS-at-Scale) (£6.24m, 2019-2027) (PI: Rashid)

Researchers within UoA11 contribute strongly to the leadership of other CDTs:

- CDT in Digital Health and Care (Co-I Santos-Rodriguez, £6.3m, 2019-2027) - see under UoA12.
- CDT in Future Autonomous and Robotic Systems: FARSCOPE CDT (Co-Director Liu, £4.8m, 2017-2028) - also under UoA12.
- Neural Dynamics (Co-Director: Houghton, Wellcome Trust, 2016-2023).
- VI-Labs was also a key partner in the EU FP7 Marie Curie ITN 'Provision'.

Combining existing CDTs and Doctoral Training Partnerships, the Faculty's doctoral training funding from EPSRC totals over £65m, £24m of which directly involves UoA11 (several of the CDTs span both UoA11 and UoA12 and have Co-Directors from both UoAs). Together with financial and in-kind support from industry and institutions, funding for postgraduate training exceeds £100m. We have been awarded 10 Industrial iCASE studentships. UoA11 has 129 current PGR students and graduated 174 PhD students between Aug 2013 and July 2019.

Recruitment

CDT recruitment is managed by centre directors and managers. Non-CDT studentships are overseen by the Faculty Postgraduate Director (Howden, UoA12) and two School Postgraduate Directors (Marshall in SCEEM). All PGR applications are reviewed by at least three academic staff who have all undertaken EDI training. Greater awareness of the importance of diversity led to an increase in the recruitment of female and BAME students (see Table 1).

Table 1: Gender and ethnicity of PGR students in UoA11.

	Ethnicity			**Gender**		
Year	**BAME**	**White**	**Not Known**	**Female**	**Male**	**Other**
2013/14	29.6%	66.7%	3.7%	18%	82%	0%
2014/15	32%	64%	4%	16%	84%	0%
2015/16	26.9%	69.2%	3.8%	16%	84%	0%
2016/17	30.8%	65.4%	3.8%	19%	81%	0%
2017/18	29.6%	63%	7.4%	19%	81%	0%
2018/19	34.5%	58.6%	6.9%	24%	76%	0%
2019/20	32.4%	61.8%	5.9%	26%	74%	0%

Monitoring and Support

All students are supported by at least two supervisors. They can be from different departments or disciplines but at least one must have already supervised a PGR student to completion. We encourage industrial supervisors and international partners. Joint supervision benefits the student, provides valuable training for research staff and is an excellent collaborative interdisciplinary mechanism which enriches the student experience. Progress and support are reinforced by annual progress monitoring comprising a written report and interview (involving an independent assessor and interviewer) with detailed feedback.

All postgraduates belong to a research group. Postdoctoral researchers are outstanding role models, for example, leading seminar series, delivering training courses and championing public engagement activities. A Faculty PGR conference, run by PGR students, has been run for the past two years to showcase the depth and breadth of research and allow students to get to know each other. Many CDTs also run their own conferences, with a focus on engaging with industry partners.

UoA11 has a large number of PGR students completing their studies each year (Table 2). The growing number of students have led to a vibrant PGR community.

Table 2: Doctoral awards and PhD students.

Year	Number of doctoral awards (data from HESA)	Number of students (all years)
2013/14	28	70
2014/15	22	73
2015/16	18	71
2016/17	23	84
2017/18	19	86
2018/19	18	103
2019/20	15	129

The total number of doctorates awarded to students with supervisors from UoA11 over the REF period was 174, approximately 30 more than the total attributed to UoA11 from Table 2. This reflects positively on the frequency of inter-disciplinary collaboration and the degree to which co-supervision occurs with academics outside of UoA11.

Research and Skills Training

Students have mandatory talks covering induction, safety, facilities, and laboratory practices. CDTs offer bespoke courses (mandatory for CDT students) and we facilitate PGRs to be co-trained with CDT cohorts wherever practicable. Students are encouraged, where appropriate, to attend specialised MSc taught courses offered at Bristol.

As described in the REF5a, in addition to discipline-specific training, our students can access a wide range of skills and career support offered by the Bristol Doctoral College. The Personal and Professional Development (PPD) programme offers the following professional support to all our research students:

- networking opportunities
- information on research grants
- a bespoke online progress management tool
- training in personal development and wellbeing
- professional and career development
- guidance on responsible research
- training in conference presenting, CV writing, research ethics, public engagement, etc.

UoB's Careers Service Postgraduate Employability Advisor supports PGR students in identifying career options and preparing for the world of work. PGR students are encouraged to get involved with the Bristol PLUS award which is designed to enhance employability. Many of our graduates continue in research, 64% as PDRAs and 27% in industry or government.

PGR students can work with the Basecamp Enterprise Team, who support start-ups and help develop enterprise and entrepreneurial skills. Through the New Enterprise Competition students pitch for start-up funding and UoB is a founding partner of the world's top university business incubator, SETsquared, and the award-winning Engine Shed (see REF5a). Many of the CDTs provide bespoke enterprise and entrepreneurial training, such as the CDT in Cybersecurity, which incorporates an industrial placement.

Promotion of equality and diversity

The Faculty actively fosters and celebrates a diverse body of staff and students by implementing UoB EDI policy and through its own local practices. CS&I is well-known for having disproportionately male practitioners and we are committed to achieving 30% female representation among staff and students by 2030. CS&I has an international demographic; 21.4% of the Faculty's academic and research staff have a Black, Asian or Minority Ethnic (BAME) background, mainly being overseas staff. Whilst we celebrate our international appeal, we strive to increase the proportion of academics from the UK BAME community. Among our 62 UoA11 academics, 17.7% identify as female (increase from 9.5% in REF 2014) and 11.3% have a BAME background (11.9% in 2014).

Examples of our commitment to EDI:

- Faculty EDI committee established and chaired by the Dean with representatives from academia, technical and professional services, the student body, LGBT+ community, unions, Women and Non-binary staff network and the Black Asian and Minority Ethnic staff network.
- School EDI Champion (Philamore UoA12) is a member of the SCEEM Senior Management Team.
- Needs of staff with caring responsibilities and health issues are accommodated. Part-time and job-share roles are increasing (two senior staff, one of whom was promoted to Professor while on a part-time contract). UoB also supports academics returning from part-time to full-time employment. Research funding (up to £10k) from the Returning Carers Scheme has supported three academics from UoA11.
- We shared with all line managers information to support staff returning from family-related or compassionate leave related to Covid-19, in recognition of the additional challenges facing staff.

- Staff with caring responsibilities can claim additional costs involved in attending conferences and interviews.
- A new initiative, 'Engineering Includes Me', inspires staff and line managers by demonstrating the benefits of supporting staff with diverse needs through case studies that promote flexible working and other support mechanisms.
- Female representation on all promotion panels helps ensure that time taken for parental leave or flexible working is properly considered.
- We actively support participation in the Aurora and Bristol FLI (Female Leaders Initiative) programmes, as well as the Bristol Women's Mentoring Network. This enabled SCEEM to increase the number of female academics in senior leadership positions: Faculty PGT Education Director (Cater), Associate Dean for Temple Quarter Research & Enterprise (Liu), Head of Research Group (Roudaut).
- Set up a system for reporting micro-aggressions, which was superseded by a UoB-wide report-and-support tool.
- Created a Women and Non-binary Staff Network for Faculty of Engineering and a network for BAME staff jointly with the Faculty of Science.
- Provided trans-awareness training to staff.

The Black Lives Matter movement persuaded us that to effect real and lasting change we must be not merely neutral (non-racist/non-sexist/non-discriminatory), but actively anti-racist/anti-sexist/anti-discriminatory. There is a new appetite within the Faculty to listen to those who have been disadvantaged as a result of inequality, to take effective action and to make a concerted effort to reduce the number of micro-incivilities that people endure. We are determined to make our processes equitable, to make it clear that we value diversity and to make everyone feel welcome in our community.

Creating a Positive Working Environment

We want our people to feel valued in their work and to feel supported in managing their own wellbeing as well as their research, impact, and education activities. Our initiatives include:

Wellbeing:

- Protected Thursday afternoons: email-free time so staff can prioritise their work.
- Weekly staff yoga sessions funded by the Faculty.
- Staff encouraged to sign up to the UoB's email charter, to lessen the burden of email.
- Virtual coffee sessions and quizzes during lockdown.

Space and facilities:

- Wellness room. A lockable room to express milk, breastfeed, pray, or rest (for those with long-term conditions).
- A new café space, meeting places, accessible gender-neutral toilets have promoted a sense of solidarity and inclusivity.
- New teaching and seminar spaces have triple hearing loops, desk and lectern risers and automatic doors, making them fully accessible.

Community building:

- Social gatherings are organised within core hours (School meetings, female and non-binary lunches, morning/afternoon coffee sessions).
- Family-friendly Faculty parties within core hours.

Meetings:

- All decision-making meetings take place in core hours.
- A protected slot at monthly School meetings enable staff members to raise issues for discussion at School level.

EDI considerations for REF submission

The REF submission itself was constructed with the primary goal of describing our research excellence across UoA11. This included the SCEEM Research Committee explaining and supporting the process for assessing independence to potential PDRA applicants. Heads of Group guided academics in writing the 100-word output statements. Extra unconscious bias training was provided to the UoA coordinator, and this informed the design of the internal review process for outputs. All review panels were representative of the makeup of staff in SCEEM, including female and BAME academics.

3. Income, infrastructure and facilities

Research funding and strategies for generating research income

UoA11 offers colleagues

- an excellent physical infrastructure in which to undertake research - one which was augmented during this REF period by substantial UoB investments
- an excellent research support infrastructure, for grant winning, industrial collaborations

These features are reflected in a substantially improved grants record and CDT achievements reflecting not only the reputation and quality of our research, but also our success in building new collaborations around the globe. Our total research income over the REF period was £39m.

Our strategy for research funding incorporates:

- Supporting the vitality of research groups to enable them to develop a strong research income stream. Each group produces a five-year plan (updated on an annual basis) that is discussed with the Head of School and School Research Director.
- Encouraging individuals to apply for externally-funded fellowships to realise their research vision, from early-career to professorial level, and spanning basic research to industrial/international secondments.
- Investing in capital and equipment funding to underpin our current and future ambitions. A key example is the Research England RPIF bid which secured £29m of capital funding for BDFI which will be based in TQEC.
- Maximising the leverage achieved by significant grants by investing in equipment, academic posts, research support posts, studentships, and technicians. UoB supported the MyWorld project with £3.7m of investment. Other successful bids have been supported by a total of more than £1m and two academic posts.

- A Major Bids Process managed by RED that supports applications for major grants through internal peer review and administrative support, for example, for ERC grants (Cristianini, £1.2m, and Smart, £1m), EPSRC (Oswald, £1.2m, Cater, £1m, McIntosh-Smith, £3m and £6m) and H2020 (Pamunuwa, £2.83m [Bristol £524k])
- Providing internal pump priming and "Idea Accelerator" funding to researchers exploring new research ideas or directions to underpin future grant applications, for example by supporting conference travel or small equipment purchases.

Table 3. External research income of UoA11 over the REF period.

Funding source	Amount
EPSRC	£18.71m
Other research councils	£1.90m
Charities	£1.34m
Industry	£2.18m
EU government bodies	£8.98m
Other	£5.94m

Evidence for the success of this strategy can be found in the following achievements:

- Capitalising on major funding opportunities from a variety of funders such as RPIF (£29m award), Innovate UK Strength in Places (£30m award), WECA (DETI, £250k), EPSRC Prosperity Partnerships (TB-Phase with Thales, ASiMoV with Rolls-Royce), Platform grants (Vision for the Future, £1.35m), EU Horizon 2020 (19 grants, £9m income).
- The EPSRC CDTs which are led or co-led by UoA11 staff, totalling c. £24m.

Other significant awards listed by research group:

- **C&C:**
  - CyBoK: Cybersecurity Body of Knowledge (NCSC, 2017-2021, £2.34m, Rashid) Implementing Multi-Party Computation Technology (ERC Advanced Grant, 2016-2021, £1m/2.5m Euros, Smart)
  - Leakage Aware Design Automation (LADA): Tools & Techniques for Software Crypto Implementations (EPSRC, 2016-2020, £1.2m, Oswald/Page)
  - SCARV: a side-channel hardened RISC-V platform (EPSRC, 2018-2023, £1m, Page)
  - Why Johnny doesn't write secure software? Secure software development by the masses (EPSRC, 2018-2021, £854k, Rashid)
- **VI-Lab:**
  - ISCF/AHRC Bristol and Bath Creative Industries Cluster (Bull) £6m
  - Vision for the Future (EPSRC Platform Grant, 2015-2020, £1.3m, Bull)
  - GLANCE: GLAnceable Nuances for Contextual Events (EPSRC, 2016-2021, £807k, Mayol-Cuevas)
  - An Integrated Vision and Control Architecture for Agile Robotic Exploration (EPSRC, 2015-2020, £754k, Mayol-Cuevas)
  - Assessment of Sea Surface Signatures for Naval Platforms Using SAR Imagery (EPSRC, 2018-2021, £720k, Achim)

- UMPIRE: United Model for the Perception of Interactions in Visioauditory Recognition (EPSRC, 2020-2025, £1m, Damen)

- **AI&I:**
  - Thales-Bristol Partnership in Hybrid Autonomous Systems Engineering (T-B PHASE) (EPSRC, 2017-2022, £2.1m, Bullock/Wilson)
  - Think Big (ERC Advanced Grant, 2014-2019, £1.2m, Cristianini)
  - CHAI: Cyber Hygiene in AI enabled domestic life (EPSRC, 2020-2023, £393k, Liu (part of a 5-institution grant of total value £1.9m).
- **BIG:**
  - Virtual Realities - Immersive Documentary Encounters (EPSRC, 2017-2020, £1.1m, Cater)
  - Cross-modal Interactive Tools for Inclusive Learning (EPSRC, 2015-2021, £706k, Metatla)
  - Interaction Design with Functional Plastics (EPSRC, 2015-2019, £1.6m, Fraser).
  - Refactoring Energy Systems (EPSRC, 2017-2022, £953k, Chitchyan)
- **FoC:**
  - GW4 Tier 2 HPC Centre for Advanced Architectures (EPSRC, 2016-2021, £3m, McIntosh-Smith)
  - GW4 Tier-2 HPC Centre for Advanced Architectures (EPSRC, 2020-2023, £4.1m, McIntosh-Smith)
  - Next generation pattern matching (EPSRC, 2013-2019, £941k, Clifford)
  - ZeroAmp (EU H2020, 2020-2024, £2.83m [Bristol £524k]) Pamunuwa).

Organisational infrastructure supporting research and impact

As part of our strategy, several policies help our academics succeed in their competitive funding applications. As noted in the REF5a, the RED Partnerships Team provides advice on fellowship and major funding bids, as well as interview training and mock panel interviews, equipment bids and programme grants. When fellowship candidates are invited to interview, RED organises interview training and mock panels with senior staff. The Faculty's ESPRC fellowship success rate over the REF period is 36.4% (national success rate is 21%) with seven EPSRC fellowships awarded to UoA11 academics in the REF period, of a total of 18 externally-funded fellowships.

In 2019, the Faculty introduced a formal pre-submission process for grant applications. It ensures that space, technical and project management support and any funding leverage are agreed by the relevant senior managers. It also provides all academics with internal peer review, feedback and support in writing funding applications, thus ensuring they have been prepared to the highest-possible standard. The ILO includes a team of 44 professionals providing post-award support, including project management, for major research activities.

Infrastructure and Facilities

The Faculty has enjoyed significant strategic expansion during the REF period with ongoing major investment to our estate. A new wing (>£19m) was added to one of the two main Faculty buildings in 2017, enhancing both our teaching and research spaces. Two research groups in UoA11 have moved into brand new office/research spaces in a newly acquired building in 2019 (1 Cathedral Square - 1CS), with more groups due to follow. UoB invested more than £1.7m in specialised facilities for UoA11 in the last six years. 1CS has been upgraded with research facilities, including computer vision labs, at a cost of £3.49m. Another building on the campus was repurposed for the

Engineering Mathematics Department and its associated research staff. UoA11 has benefitted from a rolling programme of investment in facilities, equipment and refurbishment, run through the Faculty Space and Equipment Committee.

TQEC will provide new facilities and offices for around 33 current academic staff from UoA11 (AI&A, C&C, VI-Lab, BIG) and around 20 additional academic posts, supported by capital investments relating to BDFI (£29m), MyWorld (£30m), and QTIC (£35m, UoA12).

Specialist research infrastructure investment: UoA11 uses UoB-level equipment and infrastructure, including:

- The Advanced Computing Research Centre (ACRC), which hosts the BlueCrystal supercomputers. Phase 4, featuring in the Top 500 supercomputers in the world in 2016, includes around 16,000 cores and 64 NVIDIA P100 GPUs resulting in a peak 600 teraflops of performance. In 2014 Bristol became an Intel Parallel Computing Center (IPCC), the first such centre in the UK and the seventh worldwide. As part of this initiative, we are working with Intel to modernise HPC codes so that they are ready for future many-core systems. This work involved many important contributions from the HPC group, including development and optimisation of key applications and mini-apps on Intel architectures, to leverage the advanced technologies of Intel's Xeon Phi including high-bandwidth memory.
- The high-performance computer infrastructure (Blue Pebble) runs parallel to BlueCrystal and supports the centralised purchasing and maintenance of individually-owned computer resource, allowing research groups and researchers to easily purchase, for example, GPU nodes without having to dedicate time to set up and run their cluster. This facility is in heavy use by AI&A, particularly for machine-learning applications. The Centre Strategy commits £2m per annum to meet the increasing demands of AI, big data and simulation resources across UoB.

Examples of specialised infrastructure at group level:

Isambard HPC maintains an experimental cluster of some of the fastest and most exotic GPUs and accelerators in the world. In 2017, led by Simon McIntosh-Smith, the GW4 Alliance, along with partners Cray Inc. and the Met Office were awarded £3m by EPSRC (and a further £4.1m in 2020) to deliver a new production Tier 2 HPC system for UK-based researchers. The 'Isambard' system is exploring multiple advanced computer architectures, including 64-bit ARM, and focusses on exploring the performance of the UK's most-used HPC codes. We have recently signed a strategic partnership with the Met Office and are in the process of appointing a seconded member of the Met Office to UoA11.

BRL: The most comprehensive academic centre for multi-disciplinary robotics research in the UK. UoA11 staff lead four of the seventeen research themes at BRL: Robotic Vision (Mirmehdi co-lead); Swarm Robotics (Hauert); Tactile Robotics (Lepora) and Verification and Validation for Safety in Robots (Eder). The BRL is a collaborative partnership with UWE and home to a vibrant community of over 300 academics, researchers, and industry practitioners. Together, we are world leaders in current thinking on service robotics, intelligent autonomous systems and bio-engineering. The BRL's state-of-the-art facilities cover an area of over 4,600sqm and include full mechanical workshops, wet-labs, rapid prototyping facilities, an ambient assisted-living studio, flying arena, a 16,000L test pool and 3 Vicon 3D positioning systems.

VI-Lab facilities: Newly-refurbished offices and labs at 1CS provide approximately 280sqm of researcher office space alongside 100sqm of new studio and subjective testing spaces, equipped with state-of-the-art acquisition, lighting and display equipment.

Critical National Infrastructures (CNI) Testbed: A class-leading cyber security testbed for studying CNI and IoT security with a wide variety of devices and components to model a range of networks and deploy and test the effectiveness of security tools.

Hardware Development and Analysis Laboratory: Supports work in the applied field of cryptographic engineering.

MyWorld: This grant is transforming the creative sector in Bristol and Bath by creating world-leading accessible research facilities, including an instrumented auditorium, an intelligent research studio with gallery, a motion, activity and volumetric capture suite, an edit room, a subjective testing suite including a psychophysics laboratory, an immersive-technologies laboratory, and a deep-learning suite, alongside extensive office space researchers and partners.

BN: Neuroscience, psychology and psychiatry at UoB is coordinated across bioscience, physical science and clinical departments and NHS Trusts by the interdisciplinary research network BN (460 students, PDRAs, fellows and tenured staff; total research income £55m). BN's hubs and themes unify neuroscientists from molecular, cellular, physiological, psychological, computational, engineering, digital health, epidemiological, and clinical backgrounds. BN is therefore able to draw on, and contribute to, over £60m of investments in Bristol's world-class £7.5m Elizabeth Blackwell Institute for Health Research, Animal Services Unit (£1m update in 2020), Wolfson Bioimaging Facility, £16m High Performance Computing Centre, £16m EPSRC Sensor Platform for Healthcare in the Residential Environment (SPHERE) project, £10m MRC Integrative Epidemiology Unit, £21m NIHR Biomedical Research Centre, £6.2m (from UoB, MRC and BHF), Translational Biomedical Research Centre, the Bristol Brain Centre at Southmead Hospital and the new Bristol Health Partners Academic Health Science Centre, created in 2020.

BIG offers a state-of-the-art workshop to build interactive prototypes, with the latest in 3D-printing and laser-cutting machines and an aerosol jet X5 printer, a machine unique in the UK, allowing 3D-printing of ink such as conductive ink or macrocapsules on 3D surfaces; total spend £800k plus £170k on building works. The BIG facility also offers a strategic environment to start and explore new industrial opportunities, such as Handaxe (www.handaxe-cic.com) and Ultraleap (Ultraleap.com).

The Faculty's Technical Services team (67.4 FTE) provides expert support to enable the smooth and safe running of labs, workshops and research facilities.

Use of cross-HEI UK/Overseas research infrastructure

ARCHER is the UK National Supercomputing Service which provides an invaluable resource for researchers who study problems with a global impact. It is also part of the PRACE initiative, giving leading scientific users access to a European pool of supercomputers. McIntosh-Smith used ARCHER during the ASiMoV project and is a member of the Project Board for the delivery of its successor, ARCHER2.

Microelectronics researchers make use of a foundry based in Cardiff University through the GW4 equipment-sharing framework.

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

Research Collaborations

The ILO links industry partners to academic expertise, helping to facilitate new collaborations whilst also providing stewardship to support and develop long-standing collaborations with key partners across multiple research areas. It also hosts Faculty-wide research showcase events that celebrate both the breadth and depth of our research and enables existing and new industry contacts to engage with our academics and learn about the latest developments.

Within UoA11, examples of industry collaboration include the staff secondments and joint appointments described in Section 2, and additionally Cartlidge's Senior Lectureship sponsored by Refinitiv, Bullock's Toshiba Chair, partners involved with the CDTs (c. 10 each), leading a UoB-wide data science partnership with LV=GI, Prosperity Partnerships with Thales and Rolls-Royce, an academic partnership with the Met Office, and continued engagement with companies which were spun out of UoB (e.g. Ultraleap, XMOS, Graphcore). We are an ARM Centre of Excellence, Centre of Excellence for Cybersecurity Research (ACE-CSR) and have the only UK strategic relationship with Netflix.

We capitalise on dedicated funding opportunities both within UoB (such as the Benjamin Meaker Distinguished Visiting Professorships and the International Strategic Fund - five and four awards respectively) and from external funding bodies (such as H2020 and Global Challenges Research Fund) to facilitate collaborations with academic and industrial partners based outside the UK.

Table 4 shows that most of UoA11's outputs are the result of collaboration and, as is often found, papers with wider collaborations attract more citations.

Table 4. UoA11 REF outputs by collaboration type.

Metric	%	No. outputs	Citations	Average number of citations/ publication	Field-weighted citation impact
International Collaboration	47.9%	58	1723	29.7	5.36
UK collaboration	22.3%	27	708	26.2	3.65
Intra-institutional collaboration	28.1%	34	596	17.5	3.77
No collaboration	1.6%	2	36	18.0	3.88

Relationships with research users

We encourage all researchers to actively engage with the public through a range of channels:

- Faculty and UoB blogs, social media accounts and press releases
- academics' individual social media accounts (e.g. Hauert has 5,600 followers on Twitter and she is president and co-founder of @Robohub, a non-profit dedicated to connecting the robotics community to the world which has 21,300 Twitter followers)
- travelling series of lectures in large venues, each attracting audiences of 1,000+ schoolchildren via GCSE Science Live and Science in Action (Cliff)
- writing children's books (Lepora)
- public lectures on the web (Hauert)
- appearances on radio and TV, including presenting and co-authoring an award-winning one-hour science documentary 'The Joy of Logic' for BBC4 (Cliff).

Our researchers take part in Pint of Science, Cafés Scientifiques and the Bristol Neuroscience Festival. Houghton choreographed a dance describing mathematical ideas in the work of Beckett which was performed by the John Scott Dance company and reviewed in national papers - the video of the work attracted 9,000 views.

VI-Lab played a key role, working with the Bristol Mayor and colleagues across the creative sector, in attracting Channel 4's new Creative Hub to Bristol. VI-Lab won the IEEE International Grand Challenge for Video Compression in 2017 and related work on video coding was applied by the BBC in creating programmes such as Blue Planet 2. This led to an MPEG VVC submission on Deep Visual Compression (ranked as one of the highest single-tool gains) and led to an invitation (Bull) to participate in the Alliance for Open Media.

Media appearances include:

- BBC Joy of Data (2016): Cliff and Flach
- EU Parliament, BBC Radio: Cristianini
- New Scientist Live: Hauser
- Venice Film Festival 2019: Cater
- BBC News Tonight, BBC Politics Live, German and Austrian national radio, print interviews (Wired.com, New Scientist, The Verge): Schien
- BBC Radio, BBC Digital Planet and Discovery Channel with interviews in The Economist, IEEE Spectrum, New Scientist, El Pais (Spain), and Vocable Magazine (France): Mayol-Cuevas
- Impossible Garden (exhibition in Bristol Botanic Garden), BBC and Local news: Bull
- OneShow (BBC) coverage of Friesian Cattle Identification: Burghardt

Wider Contributions to Society

- Board of Directors of Unbound Tech (Smart, 2013-2019)
- Advisor to Enveil (Smart, 2017-present)
- Zama (Smart, 2020-present)
- Cosmian (Smart, 2019-present)
- Advisor to SETL (Smart, 2016-2019)
- Consulting to Unrest Ltd, Lux Health, and Airbus (Flach, 2016-2019)
- Scientific Advisory Board of Adarga and XMOS (Flach, 2019-present)

- Consultant for Diffblue Ltd (David, 2017-2019)
- Consultant for Semafone Ltd (Dupressoir, 2018)

Sustainability of the Discipline

The CDTs are training a new generation of interdisciplinary researchers and future leaders. For example, the Cybersecurity CDT trains students to develop interdisciplinary approaches to tackle TIPS issues in the large-scale, hyper-connected infrastructures of the future. In the REPHRAIN project, a cybersecurity toolbox is being developed as a one-stop shared set of resources for researchers, practitioners, policymakers, regulators, and citizens. This will allow the public to contribute to a world-first Privacy Enhancing Technologies (PETs) testbed, datasets, benchmarks, reference scenarios and validated novel tools, method and prototypes. VI-Lab is a key partner in BVI, an internationally-leading interdisciplinary collaboration of some 160 researchers across computer science, engineering, psychology, biology, medicine and the creative arts.

A key part of the research vision for TQEC (see REF5a) is to build on our expertise in application-based research to pioneer a co-creation and co-production approach across social, computer sciences, engineering and the arts, to bring researchers together with industrial and civic partners to define new methods for sociotechnical innovation and address cross-sector challenges. This is supported by UoA11's involvement in flagship activities, such as the CDTs, BDFI, MyWorld, and REPHRAIN. Special facilities will be constructed in the next two years, including a co-creation research arena, public engagement spaces, and a reality emulator to enable sociotechnical research at realistic conditions and scale. These facilities are complemented by a Digital Health hub (to support 'in the wild' testing of devices and systems) and an immersive auditorium for large scale audience experience evaluation, based on a fusion of physiological measurements and collective behaviours to assess immersion.

Influence and Recognition

Editors and editorial boards:

- Editors in chief:
  - Machine Learning (Flach)
  - IET journal of Computer Vision (Mirmehdi)
  - Cyber Security Body of Knowledge (Rashid)
- Associate editors:
  - IET Computer and Digital Techniques (Nunez-Yanez)
  - Pattern Recognition (Damen, Mirmehdi)
  - Pattern Analysis and Applications (Damen, Mirmehdi)
  - International Journal of Computer Vision (Damen)
  - IET Computer Vision (Burghardt)
  - IET Software (David)
  - IEEE Transactions on Computational Imaging (Achim)
  - Digital Signal Processing (Achim)
  - IEEE Trans CSVT (Bull)
  - IEEE TPAMI (Damen)
  - Special Interest Group for Computer Interaction (Metatla)

- Editorial boards:
    - IEEE Transactions on Image Processing (Achim)
    - Remote Sensing (Achim)

Learned societies:

- European Association for Data Science (Flach President, 2018)
- International Association for Cryptologic Research (Smart Vice-President, 2014)
- British Machine Vision Society (Mirmehdi Executive Member, 2000)
- IET Vision & Imaging Network (Mirmehdi, 2014)
- Bio Imaging and Signal Processing Technical Committee of the IEEE Signal Processing Society (Achim, 2014-2015)
- IEEE Geoscience and Remote Sensing Society's Image Analysis and Data Fusion Technical Committee (Achim, 2007)
- UK DSTL ISTAR Concepts and Solutions Panel (Bull, 2015)
- HEFCE REF2014 UoA-13 panel member (Bull)
- IEEE Image, Video and Multimedia Tech Committee (Bull 2016)
- Governing Board member of the IAPR (Mirmehdi)
- Marie Curie Alumni Association (Nunez-Yanez, 2010)
- EPSRC, Royal Society grant colleges and the EU Eureka network of review experts (Nunez-Yanez, 2015)

National advisory roles:

- Academic Advisory Board for the UK Financial Conduct Authority (Cliff)
- UK Government Office for Science Blackett Review of Financial Technology in the UK (Cliff, 2014-15)
- Advisory Board for the UK Financial Services Knowledge-Transfer Network (Cliff, 2010-2014).
- EPSRC ICT SAT (Liu, 2017-2021)
- EPSRC Digital Economy SAT (Rashid, 2017-2021)
- Chair of Scientific Advisory Board for the EPSRC-NCSC Research Institute on Science of Cyber Security (Rashid, 2019-present)
- EPSRC's e-infrastructure SAT member, (McIntosh-Smith, 2011-2014)
- EPSRC Strategic Advisory Network (Bull, 2014-18)
- Steering Group of EPSRC funded "Network on the V&V of Autonomous Systems" (Eder, 2015-present)
- REF2021 Institutional Level Environment Statement Pilot Panel member (Liu)
- Member of the Royal Society Dorothy Hodgkin Fellowship Panel (Eder, 2018-present)
- Member of the UKRI Future Leader Fellowship peer review college (McIntosh-Smith, 2018-present)
- Steering Group member of the Innovate UK, Technology Strategy Board (Eder, 2012-2016)

International advisory roles:

- Invited by the UK government (BEIS) on the recommendation of EPSRC to be one of the UK's two representatives on the European e-infrastructure reflections group (e-IRG) (McIntosh-Smith, 2018-present)
- Member of two international standards bodies: Khronos' OpenCL, 2012-present, and OpenMP Architecture Review Board (ARB) 2016-present (McIntosh-Smith)

- Advisory board of the ICTFootprint.EU H2020 project (Schien, 2016-2019)
- Member of Amazon.com's Academic Advisory Council (Mayol-Cuevas, 2018-present).

Major Fellows:

- FBCS (Cliff)
- FRS, FREng (May)
- FIEEE (Bull, Pitas), FIET (Bull)
- Fellow of the International Association of Cryptologic Research (Smart)
- Fellow of the International Association for Pattern Recognition (Mirmehdi)
- Fellow of the British Machine Vision Association (Mirmehdi).

Awards and prizes:

- IEEE Video Compression Grand Challenge winner (Bull, Zhang, Afonso)
- HPCwire Readers' Choice Award for Outstanding Leadership in HPC (McIntosh-Smith)
- Samsung Electronics' Global Research Outreach Award (Mayol-Cuevas)
- Google Faculty Research Award (Bull)
- Outstanding Reviewer, CVPR (Damen)
- Best Oral Presentation Award Committee Picture Coding Symposium 2019 (Katsenou)
- HPCwire Readers' Choice Award - 'Best HPC Collaboration: Academia/Government/Industry' (McIntosh-Smith)
- CloudLightning's list of the 20 most influential people in HPC and Supercomputing (McIntosh-Smith)
- R&D 100 award (McIntosh-Smith in collaboration with Sandia National Laboratory, AWE Ltd, and Warwick University)
- IBM best paper (Smart, 2014)
- AHA conference with FPGA instrumentation for low energy computing (Nunez-Yanez, 2014)
- ICALP best paper (Lapinskas, 2016)
- Best paper Applied Reconfigurable Computing conference (Nunez-Yanez, 2016)
- IPEC best paper (Lapinskas, 2017)
- Best paper IEEE Computational Intelligence for Financial Engineering (Cliff, 2018)
- Best paper CUG 2019 award in Montréal, Canada (Simon McIntosh-Smith, 2019)
- Winner of basic and clinical sciences category - British Medical Association book awards (Lepora, 2019).

Conference Organisation

We have provided **general conference chairs** for:

- IndoCrypt (2017, Smart)
- CT-RSA (2018, Smart)
- International Conference on ICT for Sustainability (2020, Schien)
- IEEE Picture Coding Symposium (2021) (Bull)

Programme chairs include those provided for BMVC (2019) and **symposium chairs** include FENS (2020).

VI-Lab staff have held 26 major conference organising committee positions including 12 general chair and five programme chair roles.

Associate chairs:

- CHI (2016, Roudaut)
- MobileHCI (2017, Roudaut)
- SIGACCESS 2020 and IDC 2020 (Metatla).

Invited Talks (selected)

Staff have delivered over 20 keynote/plenary and invited lectures including:

- ISETC2018 (Achim)
- IET ISP2015, Beyond 18, 19 and AoM Workshop (Bull)
- Intl Workshop on Vision and Control for Autonomous Drones (Calway)
- VISAPP 2019 and NCVPRIPG 2019 (Damen)
- ISICS 2020, Pattern Recognition and Computer Vision Colloquium 2015, BMVA workshop 2015, Mexican Academy of Computing 2018, Spanish Technical Committee of Computer Vision 2015 (Mayol-Cuevas)
- Ministry of Defence (Hauser)
- NFS funded Embodied Intelligence in Electronics workshop; ALIFE 2018 (Bullock)
- VIVA2020, IEEE AI Test Conference 2020 (Eder)
- PharmaTec Congress 2019 (Campbell)
- Arm Partner Meeting 2019, P3MA, US DoD/DoE workshop 2019, OpenMPCon/IWOMP 2016 (McIntosh-Smith)
- VizCHI 2019 (Metatla)
- EuroCrypt 2017 (Smart)
- BRACIS 2017, IDA 2020 (Flach)
- FLOC mentoring workshop 2018, Facebook Testing and Verification Symposium 2019 (David)
- Google and the Tyndall Centre for Climate Change on sustainable digital services (Schien, 2017).

Collaborative PGR training

Co-tutelle arrangements: Thessaloniki on MULTIDRONE project; University of Seville and Aristotle University of Thessaloniki.