Institution: University of Birmingham

Unit of Assessment: UoA11, Computer Science and Informatics

1 Unit context and structure, research and impact strategy

1.1 Overview

The School of Computer Science (the UoA) is one of seven schools in the College of Engineering and Physical Sciences*,* which in turn is one of five colleges comprising the University. We are submitting 48 Category A members of staff across 5 **Themes**, described in 1.2.

Over the assessment period, the School has strengthened its position as a major research centre and further advanced its international standing. We are among the top 10 UK computer science departments in the worldwide CS Rankings table. Ten staff were awarded prestigious personal Research Fellowships. We contributed to defining University, national and international research agendas through leadership of four interdisciplinary institutes, membership of planning and steering committees, organisation of major international conferences, and over 60 editorial board positions of international journals.

There has been major investment in staffing and infrastructure. Of the returned 48 Category A staff, 22 joined during the assessment period, and for all except four this was their first academic appointment. We have attracted young researchers from internationally renowned institutions, including Oxford, Carnegie Mellon, Princeton, and Max Planck Institutes. Investment into infrastructure and facilities (£45M+) facilitated the uptake of our research by industry and beneficiaries, and subsequent impact. We strengthened our engagement with other disciplines, including biosciences, engineering, humanities, law, mathematics and medicine.

The synergy between our fundamental and applied research has fuelled collaboration with over 80 companies, from local SMEs to major international corporations. Through patents, licences and collaborative projects, our activities impacted the automotive, robotics, cybersecurity, education, healthcare and manufacturing sectors.

1.2 Structure and outlook

An important strategy since the last REF has been consolidation of our research into five research Themes (leads underlined below): **Artificial Intelligence**, **Theoretical Computer Science**, **Cyber Security**, **Human-Centred Computing** and **Computational Life Sciences**. All have seen substantial investment in people, geared towards promising early career researchers (ECRs, 2.1.1). This has already borne fruit for interdisciplinary research (1.3.vi), income creation (3.1) and impact (1.4), and bodes well for future sustainability.

Cyber Security ("Cyber")

[Chothia, Galindo, Garcia, Ordean, Oswald, Petit, Ritter, Sinha Roy, Ryan]

Expertise covers a broad range of areas within computer security, including applied cryptography, automotive security, cloud security, electronic voting, formal verification, secure infrastructure and hardware, IoT and wireless security. Members work closely with national regulatory agencies, government departments and funding bodies such as GCHQ, National Cyber Security Centre (NCSC), Rail Safety & Standards Board, and Department for Digital, Culture, Media & Sport (DCMS); and collaborate with major businesses including Jaguar Land Rover, HP, Huawei, Microsoft, IBM, Google, Deloitte, BT and the National Grid, as well as regional partners (4.1).

The international standing of our research was confirmed by the award of *NCSC-EPSRC Academic Centre of Excellence in Cyber Security Research* in 2017. The University's Dynamic Investment Fund has injected £5M into our work, supporting delivery of three Impact Case Studies (ICS-1 automotive security, ICS-2 banking app security, ICS-3 malware detection). Five

new appointments (Galindo, Ordean, Oswald, Petit, Sinha Roy) have strengthened expertise in cryptography, security of embedded systems, hardware security and post-quantum cryptography.

2021-2026 Objectives: The future continuation of high-impact industry-relevant research is safeguarded by Garcia's Birmingham Fellowship (REF5a-3.4.1) followed by a 5-year EPSRC Fellowship, 5-year Hewlett-Packard funding for Ryan, and a joint post with Fetch.ai for Galindo. Fourteen ongoing projects, funded to a total of £3.5M by EPSRC, GCHQ and industry (HP, Samsung) will contribute to future impact in car, device (TEE, IoT) and railway security (in collaboration with the *Birmingham Centre for Railway Research and Education*, the largest university-based centre of its kind in Europe), and to legal aspects of privacy.

Theoretical Computer Science ("Theory")

[Ahrens, Backens, Chitnis, Das, Escardó, Ghica, Jung, Levy, Parker, Rahli, Reddy]

Theory is one of the largest research groups in the world focusing on the logical foundations of computer science. Our international standing allowed us to attract winners of five competitive fellowships: two Birmingham Fellowships (Ahrens, Zeilberger), two Royal Society University Fellowships (Kraus, Vicary), and a UKRI Future Leaders Fellowship (Das). New appointments in type theory (Ahrens, Rahli), theory of quantum computation (Backens), algorithms and complexity (Chitnis), verification (Rahli), and proof theory (Das) have broadened the scope of our research.

In the last two years, we secured over £2M from Research Councils, Royal Society, EU and other organisations including Microsoft (Structural Foundation for Heterogeneous Computation) and DARPA (Building Resource Adaptive Software Systems). We collaborate widely and productively with internationally leading researchers and institutions (4.1). Owing to our exceptional strength in type theory we have been playing a leading role in the emerging field of univalent mathematics through landmark publications, prolific contributions to the *UniMath* library (Ahrens, ranked 2nd for contributions) and running successful research schools (2017, 2019). Via the *Midlands Graduate School in the Foundations of Computing Science* (4.4) we have contributed to the education of over 400 PhD students and industry professionals who will sustain theoretical research into the future.

2021-2026 Objectives: We will continue to build on the exceptional depth and breadth of our research, and exploit the links that arise naturally between members around logic (Das, Jung, Levy, Parker, Rahli), type theory (Ahrens, Escardó, Ghica, Rahli), automata theory (Das, Parker), complexity (Backens, Chitnis, Das), verification (Parker, Rahli), programming languages (Ghica, Levy, Reddy) and semantics (Escardo, Jung, Levy, Reddy). This will allow us to tackle both foundational and practical problems in distributed computing, autonomous systems, probabilistic and quantum computation, among others.

Artificial Intelligence ("AI")

[Barnden, Chang, He, Kaban, Kerber, Lee, Lehre, Leonardis, Li, Mansouri, Minku, Rowe, Sloman, Sridharan, Tiňo, Wang, Yao]

This Theme integrates former separate robotics, machine learning, natural computation and computer vision groups with an increased focus on a common set of foundational methods. This has materially contributed to the University's successful partnership with the *Alan Turing Institute* (ATI, REF5a-2.1.5) and has brought £5M investment which supports five fellowships in the School (Kaban, Rowe, Tiňo, Sloman, Styles). We appointed seven young colleagues (Chang, Lehre, Li, Mansouri, Minku, Sridharan, Wang), strengthening and interconnecting research in computer vision, robotics and natural computation. Foundations of machine learning (ML) was expanded by the appointment of Lehre (who has recently been awarded a Turing AI Acceleration Fellowship) and the award of a 5-year EPSRC Fellowship to Kaban. Our AI research has significantly benefitted from School, University and EPSRC investment in Tier-2 high-performance computing infrastructure (3.4).

The significance of our foundational research can be demonstrated by the impact it has made on other disciplines: Kaban's highly cited theoretical work (ML2015, AiStats2014) found applications in genomics, medicine, meteorology, defence, computer vision, traffic optimisation and many others; Tiňo's work on learning in model space underpinned novel findings on the progression of Alzheimer's disease, gravitational waves, decision making, pharmokinetic models and metabolomics. Leonardis' and Sridharan's research on visual object tracking and grasping has contributed to the development of neurorehabilitation therapies and has been employed in robotic retrieval of nuclear waste. Lehre's and Yao's impact on the ML field is evidenced by the number of citations for papers published in the assessment period: 700+ and 9000+ respectively. Likewise, Chang's 2014-2020 work on computer vision and human-robot interaction was cited 3000+ times and Sridharan's ML-for-robotics research gained 450 citations. Since 2014, our research standing was recognised by appointments to senior university and external posts (1.3.vi) and several prestigious international awards (4.4).

2021-2026 Objectives: The strength of our foundational research and our association with more than 10 University of Birmingham institutes and centres (1.3.vi) provides huge opportunities for future theoretical, interdisciplinary and industrial work. Applied AI research will continue to contribute to security, transport, automotive, software engineering, manufacturing, society, and healthcare, with most work involving ongoing worldwide collaborations with both academic researchers (4.1) and industry, commerce and societal beneficiaries (4.2). The forthcoming Tier-2 facility for high-performance computing (3.4) will significantly enhance our capacity to tackle real-world challenges.

Human-Centred Computing ("HCC")

[Baber, Bahsoon, Beale, Gould, Hendley, Howes, Russell, Sorge, Yeung]

Three senior appointments have expanded capabilities in this Theme: Russell works in speech and language science and technology, with over 150 research papers in these areas; Baber (Sir Frederic Bartlett medal winner) specialises in sensor-based human-technology interaction; Yeung (Interdisciplinary Professorial Fellow; 0.2 FTE CS) is contributing expertise in legal and ethical implications of technological development and technology policy-making. Yeung and Howes are pursuing new ideas for human rights-centred design of AI systems (*The Oxford Handbook of AI Ethics*, 2019), an area we plan to grow in the future.

Other agenda-setting and highly cited publications in this Theme include a highly influential publication on computational rationality (Howes, TopiCS 6(2), 140+ citations) and a 'manifesto' discussing usability, societal impact and implications of cloud computing (Bahsoon, CSUR 51(5), 120+ citations). Bahsoon's ideas on self-adaptive, self-aware and self-expressive computing systems have attracted much attention, particularly in AI and software engineering communities (1200+ citations for papers published since 2014). Applied research continues to deliver societal impact: Baber and Russell's interactive system *CogWatch* for assisting rehabilitation of stroke patients is undergoing an NHS clinical trial; Sorge's research has improved access to STEM literature for millions of users with visual and print impairments worldwide (ICS-4).

2021-2026 Objectives: As the impact of computing technology and AI on all aspects of society accelerates, we will focus our research on three areas: investigating the societal impact, explainability of, and trust in, AI, jointly with our AI and CLS colleagues in natural computation, robotics, computer vision and healthcare applications; educational, ethical and governance implications of AI, building on our links with the School of Law and the *Finnish Center for AI*; and SE issues concerned with the design, building and deployment of AI-based computer systems.

Computational Life Sciences ("CLS")

[Claridge, Dehghani, Duan, Little, Styles, Terry]

This inherently interdisciplinary Theme has a scientific base in AI, mathematics and physics and aims to interpret data, including images, generated from a wide range of fields in the life sciences and medicine, and to develop practical applications benefitting bioscience research and healthcare. High-calibre appointments have broadened our expertise, opened new impact avenues and expanded connections to related disciplines: Little (statistical ML for health); Duan

(ML for medical imaging); and Terry (0.2 FTE CS, systems modelling and quantitative biomedicine, a joint appointment with Medicine and Mathematics).

We hold leadership positions in four Birmingham interdisciplinary institutes and are active members of two health-focused centres (1.3.vi). We have made noteworthy scientific contributions to the development of the field as evidenced by numerous publications in journals such as the *Nature*-group research journals, *IEEE TMI* and *Pattern Recognition*, and highly cited post-2014 papers (e.g. Dehghani: 3000+, Little: 2300+, Duan: 1000+). Our work is also impacting allied disciplines as shown by publications in diverse physics, chemistry, microscopy, genetics, and major medical journals. Our research is taken up by the healthcare and pharmaceutical industries and healthcare organisations, translating into benefits to society (4.2). We have contributed to the education of future generations of researchers through leadership of two CDTs (PSIBS, Sci-Phy, 1.3.v), the international *NIRFAST* workshops and the EU ITN *BitMap*.

2021-2026 Objectives: Our efforts will increasingly focus on the development of ML methods that lead to step changes in pre-clinical and medical imaging and data analysis, particularly in multimodal optical imaging and advanced microscopies. We will draw on novel methodologies from the AI Theme and benefit from having world-class university colleagues as biomedical collaborators. Three top-rank 2021-starters will bring fresh theoretical ideas and expand the existing interdisciplinary research links with Medicine, Biosciences and Engineering: Krull (CS lecturer), a pioneer of AI-based microscopy image denoising; Guggenheim (Royal Society University Research Fellow, joint with Medicine), the developer of a novel photo-acoustic imaging technology; and Wheeler (Interdisciplinary Birmingham Fellow, joint with Health Sciences), a data scientist joining from the Sanger Institute. Further collaborations and funding opportunities will arise through the Health Innovation Campus (REF5a-4.2.2), a university-wide initiative to build a state-of-the-art campus for medical research (opening in 2023).

1.3 Review of REF 2014 objectives and future strategy

Computer Science at Birmingham focuses on long-term, fundamental research challenges of relevance to the discipline and society in general. Our vision is to deliver **world-class research outputs and outcomes** with **long-lasting impact** by appointing and supporting **outstanding young researchers**, developing and attracting **research leaders**, **training the next generation** of researchers, and **engaging with other disciplines, industry and public services**, all in a **supportive, collaborative and stimulating environment**.

In the reporting period we have stayed true to this vision, and have comprehensively delivered on all the strategic objectives formulated in REF2014.

(i) Delivering world-class research outputs.

The School is placed 7th among UK departments in CS Rankings, a table based on a department's publication record in recognised top conferences. Our work also appears in some of the subject's highest-ranking journals (4.1) and scores highly on citations, demonstrating the influence of our work. Given that new starters constitute nearly half of our current staff, this demonstrates the effectiveness of our support mechanisms and places us in an excellent position for the future.

(ii) Delivering outcomes with long-lasting impact.

The four submitted ICSs exemplify the effectiveness of our impact strategy (1.4): the spin-out company Lastline (ICS-3) provides sophisticated anti-malware products protecting over 20 million users worldwide; the *Speech-Rule-Engine* software (over 1M downloads since 2015) improves access to mathematical and scientific literature for visually impaired users via tools such as Google ChromeVox (ICS-4); our cybersecurity research led to improved car security, impacting on hundreds of millions of vehicles from 33 manufacturers worldwide (ICS-1); and our (responsibly disclosed) work on banking apps protects tens of millions of users worldwide from fraud (ICS-2).

New security protocols are currently undergoing standardisation before their final deployment as a part of the European Rail Traffic Management System (4.2). Software for remote monitoring and detection of Parkinson's is used in clinical trials by leading international companies (Pfizer, UCB Biopharma). Our non-invasive screening technology for skin lesions is deployed in 35 countries worldwide. We contribute to the growth of the research base and future impact through hosting and running graduate schools and leading CDTs which, since 2014, have trained several hundred PhD students and industrial researchers (3.2). We are safeguarding future impact by actively promoting and training for entrepreneurial skills (1.4, 2.1.5).

(iii) Appointing and supporting outstanding young researchers.

We are proud to have been able to recruit young researchers from the most renowned institutions in the world, including Oxford, Carnegie Mellon, Princeton, Sanger and Max Planck Institutes. These appointments have allowed us to strategically grow research capacity in existing areas as well as establish new directions, such as type theory, post-quantum cryptography, AI for software engineering and photoacoustic imaging. 80% of our appointees are new entrants to lecturing careers. That they feature strongly in our research outputs (2.3) and grant capture (3.1), demonstrates both their high calibre and the effectiveness of our caring ethos and multifaceted support mechanisms (2.1.3).

(iv) Developing future research leaders

In addition to promoting the University's Developing Leaders programmes (REF5a-3.4.4), we have established an active support scheme (2.1.2) where grant applications are peer-reviewed by experienced colleagues, and candidates are supported by a series of mock interviews with panels including both discipline-based and external staff. In the reporting period all fellowship applicants who reached the interview stage have been successful (3.1). Promotions to Chair (8) and Reader (6) have been actively encouraged via HoS-led Performance Development Reviews (PDRs) by inviting promising colleagues to apply (2.1.2), and by actions designed to encourage minority applicants (2.1.2, 2.3). We have supported career trajectories of staff who have taken on senior management positions in the University. This includes the appointment of Styles to the role of Director of the *Institute for Interdisciplinary Data Science* and AI; Baber to Deputy Director of Research for the College, and Rowe to Deputy Pro Vice-Chancellor for Strategic Projects. They all remain full members of the School and are thus able to continue to pursue their individual research agendas.

(v) Training the next generation of researchers

We are strongly committed to and invested in training the next generation of researchers. In the REF period 218 students (146.1 FTE) graduated under our supervision, including over 40 (14.5 FTE) interdisciplinary students in two CDTs (2.2.2). The effectiveness of our training and supervision (2.2) is evidenced by the increase in PhDs awarded (+135%) and a completion rate consistently above 80%. We have contributed to the education of over 400 PhD students via the Midlands Graduate School consortium and trained tens of ECRs through the EU funded Marie Curie ITN and RISE programmes (2.2, 4.4).

(vi) Engaging with other disciplines, industry and public services

We have made great strides towards our long-standing aim of initiating, encouraging and supporting **interdisciplinary work**. We have established the *Centre for Cyber Security and Privacy*, one of the EPSRC-GCHQ Academic Centres of Excellence. We are co-founders of the *Centre for Computational Neuroscience and Cognitive Robotics*, the *Human-Computer Interaction Centre* and the USTC-Birmingham *Joint Research Centre in Intelligent Computation and Its Applications*. Styles is the founding Director of the *Institute for Interdisciplinary Data Science and AI*.

We are also active partners in the cross-institutional *Centre of Membrane Proteins and Receptors*, *Birmingham Centre for Human Brain Health*, *Institute for Metabolism and Systems Research*, *System Science for Health Consortium*, *Centre for Computational*

Biology, *Centre for Predictive Modelling in Healthcare* and the *Birmingham Centre for Railway Research and Education*.

We have co-led two CDTs, *Physical Sciences of Imaging in the Biomedical Sciences* (*PSIBS*) and *Physical Sciences for Health* (*Sci-Phy*), which provide interdisciplinary training at the interface between chemistry, physics, life sciences, engineering and CS. Each student is supervised by researchers from three different disciplines, for example: CS, chemistry and biomedicine for mapping the molecular characteristics of cancer via analysis of hyperspectral mass-spectrometry data; dentistry, CS and engineering for high-speed imaging to improve dental ultrasonic plaque removal.

Examples of individual collaborations and joint industrial, business, and public service projects are given in 4.1 and 4.2.

We have laid strong foundations for future sustainability. In addition to appointing young staff with strong interdisciplinary portfolios (Sinha Roy, Chen, Duan, Little), we helped establish two Interdisciplinary Professorial Fellow positions, in Law, Ethics and Informatics, and in Systems Modelling & Quantitative Biomedicine. Two interdisciplinary Birmingham Fellows are joining CLS. Furthermore, we have negotiated part-time contracts for five colleagues who have transitioned into an industry-sponsored research laboratory, thus fostering and facilitating the interchange of ideas between academia and industry, and opening new avenues for impact (2.1.5).

(vii) Creating an inclusive, supportive, collaborative and stimulating environment

We have maintained a culture of openness and inclusion demonstrated by open membership of School committees, prominence of EDI considerations in School business (2.3), no formal barriers between research Themes, equitable access to funding, resources and infrastructure, and peer sharing of research practices. Well-equipped research laboratories (3.4), cross-disciplinary links across campus, wide academic and external networks (4.1), collaborations and organisational structures supporting research and impact (3.2) and a supportive policy on flexible working (2.3), create an attractive working environment for all staff. Proactive career-development policies, training opportunities for professional and personal development, and measures for rewarding achievements, have made staff feel supported and the School appealing as a place of employment (2.1).

Overall, in the reporting period the above strategies have established the School as both a destination for talent of the very highest calibre and a diversity of backgrounds, and a collaborator of choice for partners from other disciplines and outside academia, thus contributing to the growth, impact and sustainability of the discipline at a national and international level. Having proved effective, **these principles will continue to guide our strategy into the future**.

1.4   Enabling impact

Since 2014, the School has seen significant growth in research with reach and impact beyond academia. This has resulted from the implementation of a four-point strategy (see below) which will continue into the next assessment period. Strategic issues are addressed here, with further details presented in later sections.

Raising awareness. Impact is formally included on the agenda in PDRs for all staff, including discussion of potential opportunities and recommendations for relevant training (2.1.5). These items are also covered in induction meetings for new staff conducted by the Head of Staff Development. University-wide developments aimed at supporting impact are channelled to the School by the Deputy PVC for Research Impact (REF5a-2.1.3).

Identifying opportunities. To proactively bring forthcoming opportunities to the attention of relevant staff we established a Research Facilitator post (3.3), complementing the University Research Development service (REF5a-4.1). To identify openings for exploitation with partners beyond academia we used opportunities presented by annual Research Days, annual Industrial Advisory Board meetings, career fairs, direct links

through colleagues with joint industrial appointments or who took senior positions outside academia, sponsors of PhD projects, etc. (2.1.5). Our investment in interdisciplinary appointments has opened up new avenues for impact. The growth of external engagements was also fuelled by our active search for partners to exploit our basic research and by addressing the needs that we ourselves have identified.

Building capacity. In recognition of the long timescales often involved in getting research "ready" for external uptake, the School has invested in lead-in measures such as specialised laboratory facilities, study leaves, small-scale grants for blue-skies investigations and travel grants for industrial visits (3).

Supporting routes to commercialisation and/or dissemination. University of Birmingham Enterprise Ltd (UoBEL, REF5a-4.1) has been an important two-way route to commercialisation and dissemination. A significant proportion of staff have benefitted from enterprise training and professional assistance leading to a significant volume of patents, licenses, records of invention and spin-out companies (2.1.5). UoBEL is also acting as a broker for businesses coming to the University to access the intellectual property, know-how and expertise available in the School, including support for PIs seeking to engage with external partners. Joint appointments and other means identified above provide direct access to industry and ease translation. We are making use of the institutional EPSRC Impact Acceleration Account and business partnering provided by Innovate UK.

The above strategies have materially contributed to both the submitted ICSs and the abundance of projects in our current impact pipeline. As an illustration: the car security (ICS-1) and secure banking (ICS-2) work benefitted from investment in cybersecurity staff and laboratory equipment (3.4); success of anti-malware products (ICS-3) has origins in the co-founding of a company by a staff member; worldwide availability of software enabling on-line access to STEM materials for the visually impaired (ICS-4) began with a study leave at Google.

Many of the collaborations (detailed in 4.2) have either already made significant impact in important business and societal areas (e.g. secure designs for IoT, contactless card security, mobile health monitoring, screening for diseases) or show strong early signs of success (e.g. trustworthy voting, supply chain security, rail security protocols, engine optimisation, vehicle route optimisation, adaptive software systems and architectures, cloud computing, imaging techniques for drug discovery, health monitoring and diagnosis).

1.5   Progress towards an open research environment

We are committed to compliance with the *Concordat on Open Research Data* and *Plan-S*, supported by the University's Open Research Group (REF5a-2.2). Data sets, postprints of all publications and theses (unless sensitive) are submitted to the institutional repository from where they become freely accessible via the University's Research Portal (REF5a-2.2, REF5a-4.5). Like many computer science establishments, we make our software available via open repositories. Examples include the probabilistic model checker *PRISM* (Parker et al., ~80,000 downloads to date), *Speech Rule Engine* (ICS-4, over one million downloads in 5 years), software for optical molecular imaging *NIRFAST* (Dehghani co-lead and developer) and the *UniMath* library of Coq code (started at Princeton with Ahrens as a key contributor). As a matter of principle, the Cyber Security group releases tools and proof-of-concept code as open source.

Our commitment to open publishing is via editorial roles at gold open access journals including *Logical Methods in Computer Science*, *Compositionality*, *Mathematical Foundations of Computing*, *Biomedical Optics Express*, *Medical Image Analysis*, *Frontiers in Psychology*, *Digital Biomarkers* and others. Where it has not been possible to publish in such outlets, we draw upon the institutional open access fund (REF5a-2.2), which complements support provided by UKRI and the Wellcome Trust.

1.6   Research integrity

We adhere to the *University's Code of Practice for Research Ethics* (REF5a-2.2), and provide bi-annual training on research integrity, GDPR and ethical self-assessment in line with the UK

National Concordat to Support Research Integrity. Training is part of the induction process for new staff (2.1.3) and the compulsory *Research Methods* module for PhD students (2.2.4). The Research Ethics Officer provides internal oversight and best practice advice. No infringements have occurred during the reporting period. As an illustration of the effectiveness of our processes see our work in applied security (ICS-1 and 2) where the protocol for responsible disclosure was followed and GCHQ/NCSC and trade bodies were informed and engaged throughout.

2   People

2.1   Staffing strategy and staff development

The School actively supports the career and professional development of its members at all stages in adherence to the three principles of the *Concordat to Support the Career Development of Researchers*: environment and culture (2.1.2), employment (2.1.1) and professional and career development (2.1.2-2.1.5).

2.1.1   Recruitment

Consistent with our decision to consolidate research around five Themes, we pursued recruitment strategies aimed at ensuring critical mass in each, broadening the scope, enhancing diversity, and building sustainability by bringing in new talent. As a result, we have expanded and strengthened all the Themes: Cyber by appointing 5 academics, Theory 5, AI 6, HCC 3, and CLS 3, with 80% of new recruits being first-time lecturers. Like existing Category A staff, all new recruits are on open contracts (which include a probationary period, 2.1.3). We were able to address succession in leadership roles internally, via promotion rather than recruitment.

Following our inclusiveness ethos and to ensure fair representation, all School academics are engaged in the faculty search process, encouraged to suggest candidates and invited to evaluate applications. Shortlisting is conducted by a group of experts in relevant areas, bearing in mind the protected characteristics of candidates. Unconscious bias and diversity training is provided to all staff. To enhance gender diversity, *all* non-male applicants are considered by the shortlisting group, irrespective of whether they were longlisted. Interview panels, chaired by a College representative, include at least two non-male staff members. The recruitment process is overseen and monitored by the School EDI team (2.3). As a result of these actions we recruited 3 female, 1 non-binary and 9 BAME academic staff members during the assessment period, significantly increasing diversity among our staff.

2.1.2   Support and development

The School supports its staff throughout all career stages, embracing a culture of collegiality, intellectual stimulation and high achievement, and respecting the principles of the *Concordat*.

There are no formal barriers between the research Themes. Attendance and membership of most School committees is open to all staff and PhD students. For example, our Research Committee has representatives from all Themes and all levels of seniority: 3 professors, 3 senior lecturers, 2 lecturers (one ECR), 2 RFs and 1 RS, of which 3 are female and 2 from ethnic minority backgrounds. The most recent meeting had 7 guest participants, 3 of them lecturers appointed in 2019.

The Head of School carries out an annual PDR for all academic staff which focuses equally on personal development and the School's strategic objectives. This includes advancing career aspirations, identifying funding opportunities, enhancing leadership skills and planning pathways to promotion. Material outcomes of these reviews are that: 29% of staff were promoted in the assessment period, including 8 to Chairs; the School has a portfolio of 9 potential ICSs (from which four were chosen for submission); and engagement with industry has significantly widened (2.1.5, 4.2).

Staff are encouraged to take advantage of the University's Developing Leaders programmes (REF5a-3.4.4) aimed at more senior academic staff, including Senior Leadership, Research Leadership, Aditi Leadership (for BAME academics) and Aurora Leadership (for female ECRs). The effectiveness of these programmes can be seen in a number of research leadership roles entrusted to staff from our School (1.3.iv).

The Workplace Wellbeing team (REF5a-3.4.5) provides an Employee Advice and Listening Service to support staff facing work or personal issues, an Employee Disability Service and an Occupational Health Service. In recognition of the commitment and work towards supporting research staff, the University's European HR Excellence in Research Award was renewed in 2016 and 2020.

2.1.3   Supporting and integrating ECR staff

The School's reorganisation around five Themes has facilitated the welcome and integration of new colleagues through mentoring, joint PhD supervision, sharing established links with industry, and encouragement to give and host weekly seminars and bring in visitors and collaborators.

New academic staff follow a personal probationary development plan (PPDP), with 50% reduced teaching and administrative loads, and are allocated a mentor to develop their initial academic objectives. Oversight and support are provided by the Head of Staff Development, a senior academic (Claridge). New starters also benefit from a pump-priming fund, a PhD studentship and prioritised access to Research Committee support funds (3.3).

An extensive induction programme is provided at School, College and University levels, led locally by the Head of Staff Development. At **School** level it comprises workshops on lecture preparation, maintaining research momentum and protecting work-home balance. To develop grant writing skills, Research Committee oversees an internal review process of draft applications. A tangible outcome of this has been that 43% of the total 2019/20 School grant capture came from projects led by new starters, although they comprise just 27% of our Category A staff. A **College**-funded scheme provides personalised coaching by an external educational expert, involving practical advice, observations, group discussions and one-to-one feedback. This is well received not only as professional training but also as a means of developing confidence and bonding. The **University's** central induction programme is delivered simultaneously to academic and professional services staff to promote future co-operation. Mandatory online training covers EDI, Information Security Awareness, GDPR, and Health and Safety.

The College offers the Postdoctoral and Early-Career Researcher Career Development and Training (PERCAT) scheme to support the PDR/ECR community, covering research, teaching, entrepreneurship, management, research funding, fellowships, interviewing and EDI. PERCAT also gives voice to ECRs when setting College strategy. The School fully respects the entitlement given by the *Concordat* for all PDRs and ECRs to spend 2 hours per week undertaking career enhancement activities.

2.1.4   Sabbaticals

All academic staff are encouraged to apply for sabbatical leave, and between 3 and 8 do so in any one year. Subject to a compelling research or impact plan, this allows them to take a term's leave after 3 years, or a full year's leave after 6 years of service. Applications are reviewed and refined by Research Committee and the Head of School, and then forwarded to the College for final approval. During the assessment period, 22 staff were granted leave. Sorge's work culminating in ICS-4 is the direct result of a one-year sabbatical spent at Google Research Labs.

2.1.5   Interchange with industry, enabling and rewarding impact

Our *strategy* towards stimulating and facilitating impact is described in 1.4. Here we describe *concrete measures* and *outcomes*. Further outcomes can be found in 4.2.

Since 2016, we have combined our annual Research Day with the meeting of the Industrial Advisory Board, leading to new collaborations and PhD sponsorships. The latest 2019 Research Day was dedicated to our Cyber Security work and attracted over 40 representatives from commercial and governmental organisations, including Facebook, Lloyds Bank, PwC, Huawei, KPMG, Honda, BAE Systems, Capgemini, HP, and the National Cyber Security Centre. This successful format will be repeated annually, the next topic covering programming languages and verification research.

In the reporting period, about a third of our academic and PGR staff attended *University of Birmingham Enterprise* (UoBEL) training sessions, including Medici Enterprise Skills seminars on topics including consultancy, collaboration with business, licensing a technology and spinning-out a company. Via UoBEL, 13 staff carried out consultancy work; 3 spin-out companies have been established (CloudTomo, 3D Engine, Mokkapot) and more are in the pipeline; 6 patent applications have been filed and granted, and a further 5 applied for; 30

records of invention have been registered, 4 new licenses signed, and 6 IP agreements granted. Sectors include automotive, autonomous robotics, cybersecurity, education, healthcare and manufacturing.

The increased openness to industry also generated new career opportunities for staff. For example, Ryan is now funded 80% by HP, Leonardis and Ghica are seconded 80% to Huawei Research Labs, and Galindo 80% to Fetch.ai. Sorge has taken his research (ICS-4) as the basis for the spin-out company Progressive Accessibility Solutions. Links back to the School have been retained to facilitate knowledge transfer and provide career opportunities for students and PGRs.

Staff whose research substantially contributed to industrial innovation, economic or societal impact were promoted to chairs (Dehghani, Garcia, Ghica, Sorge).

2.2 Support and training of research students

Our PhD student population has undergone substantial growth in both numbers and diversity. The total number of PhDs awarded increased by 135%, from 57 in the previous REF period to 134 in 2014-2019 (Covid-19 related extensions affected the 2019/20 numbers). We attract students from diverse ethnic backgrounds; the non-white proportion of PGRs stands at 63%, having grown by 71% from 38 to 65. 29.4% of our PhD students identify as female, slightly above the HESA sector benchmark of 26.9% and, typically, 16% of joiners are mature students.

2.2.1 Recruitment

The School encourages its members (especially ECRs) to advertise the availability of PhD scholarships to their research communities. Applications are received and processed by Central Admissions who at this stage do not collect information about protected characteristics thus ensuring unbiased handling. Promising applicants are interviewed by the prospective supervisor and one further academic. A team led by the Director of Postgraduate Admissions then makes decisions about offers of funding, based on academic promise and the balance across supervisors, and mindful of EDI issues.

2.2.2 Studentships

The School benefits from a wide range of sources for PhD funding. In the reporting period the EPSRC DTA funded over 20 students. More than 40 (co-supervised) students were supported by the EPSRC CDTs *PSIBS* and *Sci-Phy,* a quarter of whom benefitted from collaboration and in-kind assistance from external partners including NPL, QinetiQ, AstraZeneca, Thermo Fisher Scientific, Renishaw, and UCB. GCHQ funded 8 Cyber Security PhDs. 14 PhDs were supported by the Birmingham-SUSTech split-site programme. Six students were competitively co-funded by Birmingham-Melbourne Priestley Scholarships (REF5a-2.1.8). Industrially funded studentships were provided by, among others, Honda Europe and Jaguar Land Rover. Institutional funds were used creatively to augment externally funded projects and to provide ECRs with their first supervision experience; more than 50 PGRs were supported in this way.

2.2.3 Monitoring and support

Research students work with one or two supervisors with whom they meet on a weekly basis. A *Thesis Group* adds support of two further academics; it meets twice yearly to consider a report by the student, to engage in detailed technical discussions and to follow through a checklist of skills needs and general well-being. If any potential problem is identified, remedial action is recommended, including training or outside expert help. Thesis Group reports are subsequently reviewed and actioned by the Research Student Monitoring Group (RSMG). A key step of the monitoring process is the Thesis Proposal, a substantial report due 12 months after admission. Its acceptance by RSMG almost always indicates successful completion of the PhD programme. A completion rate well above 80% since 2007 attests to the effectiveness of our processes.

2.2.4 Skills development and career preparation

PhD students are provided with a range of opportunities to help them prepare for future careers. During their first year, they complete a formal Research Skills module run by the School. Thesis Groups refer students to training courses offered by the *University Graduate School* and the

Birmingham Academic Skills Gateway, to meet development needs in line with Vitae's *Researcher Development Framework* (REF5a-3.2). Teaching training is offered to all PGRs who work as Teaching Assistants. Subject-specific training is provided by summer schools to which several members of the School contribute (4.4), and every PhD student is guaranteed participation.

In line with the expectations of our discipline, PhD students are encouraged to disseminate their results at international conferences and to further their careers by networking at such events. The largest part of our research support fund is used to enable conference visits.

Conversely, our research students contribute to the life of the School by active membership of committees, playing a particularly important role in Research and Liaison committees. In our participative culture they feel free to take their own initiatives, contributing to the vibrancy of the School's research life. One example is *CSoC Research Training*, a PhD-led series of sessions running since 2015; in addition to science subjects, topics include research ethics, thesis evaluation, publication reviews and handling rejections. *Cake Talks*, informal meetings combining research networking and socialising, have continued since 2002 as have *Lab Lunches*. To celebrate success we have introduced twice-yearly showcasing events where recently graduated research students present their work.

2.3 Supporting equality and diversity

The University is a charter member of Athena SWAN and Race Equality Charter, holding Bronze Awards in both. It is also one of the awardees of the EPSRC *Inclusion Matters* scheme led by a School professor (Rowe). An EDI Lead (Baber) provides local leadership, supported by University and College EDI officers. Examples of initiatives, both staff- and student-originated, include posters celebrating LGBT computer scientists, naming School rooms after female computing pioneers and successfully promoting participation in the BCS Women network, Ada Lovelace Days, Black History Month and similar events. EDI is a standing item on the agenda of all the main School committees.

Over 25% of our academic staff and 63% of PGRs are drawn from ethnic minorities. 29.4% of our PhD students identify as female, but gender balance of academic staff remains a challenge. Under our new recruitment regime (2.1.1) the proportion of non-male staff in the REF period grew from a low of 2 to 5, an increase from 4% to 10%. Two female staff are professors; one was promoted in 2018 as a direct result of targeted support by the School Staffing Committee.

We actively participate in actions aimed at levelling opportunities for female staff. The School instigated female-specific grant writing workshops run by Professor Averil MacDonald. Claridge is a member of the Female Professors Network which provides input on gender-related issues to University senior management. She contributes to the University-wide seminar series *Inspiring Women*. Backens was a speaker in London Hopper Colloquium 2020.

The School implements the University's supportive policy on flexible working (REF5a-3.4.5). All requests for parenting or caring leave (from staff of any gender) were granted. Seminars and School events are timed to accommodate all members with parental duties.

Outputs for this REF submission were selected according to quality, employment status (preferring category-A), and *career stage*. As a result, 34% of our submissions are by new starters although they constitute only 29% of the author pool. The team overseeing this process underwent EDI training and followed the University's REF Code of Practice to ensure that the submission is truly representative of diversity of the School. All staff were invited to contribute to the writing of this environment template and the 2020 Research Day was devoted to a discussion of our future research priorities.

3 Income, infrastructure and facilities

3.1 Research funding and income strategy

Our strategy for 2014-2021 was to:

- make strategic appointments to diversify and access new funding streams (1.2, new CLS Theme);
- recruit talented staff with strong potential to attract research income (2.1.1);
- strengthen operational infrastructure to support staff in grant capture, from preparation to submission and post-award (3.3);
- provide staff with the time to prepare competitive applications, using supportive PDRs (2.1.2) and responsive workload management.

The successful implementation of our income strategy has led to an overall 84% increase, from £11.4M in REF2014 to £20.9M in this assessment period, with growth in all major funding streams. New starters brought in 43% of 2019/20 awards, strongly contributing to the overall 25% increase since 2018/19, and marking firm upward trajectory in the context of a large generational change in our staffing profile.
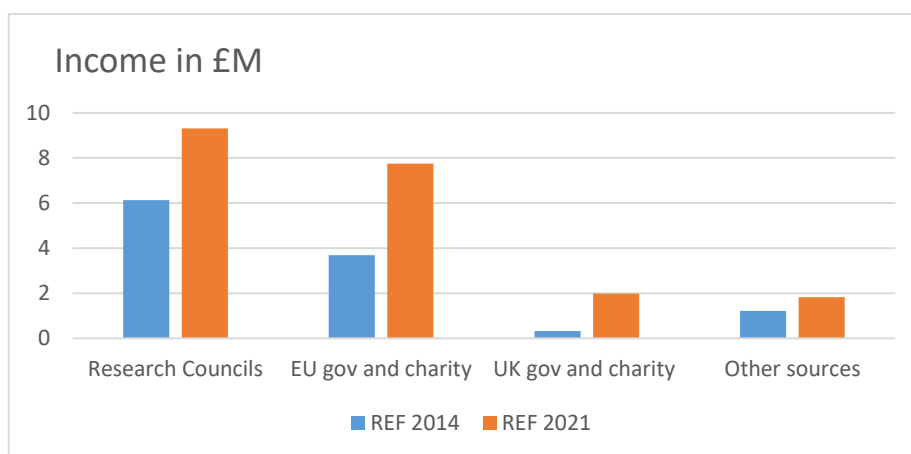
Our strategy has delivered notable successes for individual researchers (1.2) as well as cross-institutional consortia (4.1); has brought in large awards (e.g. Leonardis' £840K EPSRC computer vision grant) and smaller grants with significant impact (e.g. for the Cyber Security Lab, 3.4); and has enabled both discipline-based (e.g. Ghica's £430K EPSRC grant *Diagrammatic Languages*) and cross-disciplinary work (3.2). Proactive advertising and encouraging applications for prestigious fellowships resulted in a 100% success rate from selection to award in the last three years (3 EPSRC, 2 UKRI, 5 ATI). These achievements continue beyond the reporting period, with more than £5m in large grants captured since August 2020.

Objectives for 2021-2026 are to:

- expand our cross-disciplinary funding successes to accelerate translation of CLS and AI work, including via Birmingham Health Innovation Campus (REF5a-4.2.2);
- capitalise on the University's affiliations with the Rosalind Franklin and Turing Institutes (REF5a-2.1.5);
- build on our staff secondments (2.1.5) to grow funding from industry and governmental agencies;
- continue to support all staff to sustain success in winning high-profile fellowships and grants;
- nurture and accelerate the careers of the next generation of researchers.

3.2 Organisational infrastructure supporting research and impact

Strategic reorganisation into five research Themes has substantially increased critical mass in each Theme, improved support for research staff and enabled tighter focus on potentially impactful areas. Recruitment targeted on ECRs brought the injection of new ideas to the Themes, thus safeguarding sustainability and vitality. The laboratory-based Themes benefitted from substantial investment in infrastructure and facilities (3.4). These, in turn, contributed to increased engagement with industry and beneficiaries, and subsequent impact (4, ICSs).

Beyond the School, we play an active and leading role in many interdisciplinary initiatives across campus (REF5a-4.2.3). The *Centre of Excellence in Cyber Security Research* was created with £5M University investment, widening the scope of our GCHQ-accredited activity. Our membership of the *Alan Turing Institute,* supported by a further £5M of institutional funds, benefits the School's AI, HCC, and CLS Themes with fellowships and postdoctoral funding. The *COMPARE* consortium, aimed at developing and exploiting novel computational methods for visualising single membrane proteins, involves collaboration between Medicine, Dental Sciences, Computer Science and Chemistry in Nottingham and Birmingham, and was established through a £10M University grant. The University also invested £15M into the *Centre for Human Brain Health,* which works closely with the CLS Theme using novel computational imaging techniques to investigate neural function, and £10M into a joint initiative between the *Institute for Metabolism and Systems Research*, the School of Mathematics, and Computer Science, led by a new appointee (Terry).

3.3 Operational and scholarly infrastructure

We are housed in a modern, dedicated, and fully accessible building with offices and laboratories accommodating staff, PDRAs and research students. Open spaces, meeting rooms and breakout spaces provide the environment for small-group meetings and seminars. The 4-storey atrium is used for workshops, conference breaks and School social gatherings. Located directly opposite are the University's *Murray Centre* and the *Colab*, providing state-of-the-art laboratories.

A dedicated team of three internally managed senior computer officers provides support for both software and hardware, as well as continually developing and enhancing the computer infrastructure to meet our specialised research needs.

Proactive dissemination of funding opportunities and pre-grant support is provided by the Research Facilitator, a dedicated member of administrative staff; since her appointment, we have seen a dramatic upturn in our external funding activities and an increase in success rates. She works as part of a team of 10 research support staff at College level, itself aligned with institutional-level services (REF5a-4.1). Post-award support is provided by three officers working across the School, assisting with open-access processes and special events.

Research Committee has a dedicated budget to support research at all levels (travel, minor equipment, research visitors, workshop and summer school organisation). It also administers the *Ramsay Fund,* aimed specifically at blue-skies research and ECRs. Research Committee members are drawn from across all research Themes and are fully representative of the entire School population. Meetings are open to all staff and minutes are held in a School-accessible online repository.

3.4 Infrastructure and facilities

The School boasts three **dedicated research laboratories**, supported by grants from a wide range of funders, and enabling staff from three groups and over 60 PhD students and PDRs to engage in interdisciplinary impactful research.

The Cyber Security Lab was launched in 2014 and has since been awarded over 10 grants (nearly £1M in total) from GCHQ, enabling the provision of sophisticated equipment and capabilities to analyse embedded and IoT devices. This included in-kind donation of a Land Rover Evoque to conduct automotive penetration testing on a real vehicle. The lab is housed in a large purpose-built facility supporting 18 PhD students and PDRAs. These investments

resulted in impactful research into car security systems (ICS-1) and secure banking (ICS-2). The lab carried out numerous impactful projects: the *Plundervolt* proof-of-concept code enabled Intel to verify a vulnerability in their CPUs and resulted in them rolling out a microcode patch to all of their CPUs worldwide; the *Tale of Two Worlds* work revealed 35 vulnerabilities in 8 major open-source shielding frameworks for Intel SGX, RISC-V and others, leading to numerous security patches in the open-source projects, including the Intel SGX-SDK, Microsoft Open Enclave, Google Asylo, and the Rust compiler.

The Digital Dark Room provides space and facilities for developing novel imaging systems and for experiments requiring controlled lighting conditions for medical imaging research. At 20m^2, it houses state-of-the-art equipment including several large optical tables, 3D printer, 3D camera, integrating sphere, microscopes, calibrated light sources, spectrometers, and components for constructing bespoke optical imaging systems. The lab is used by academic staff and over 20 PhD students and PDRAs. It has secured over £3.5M in grants from EPSRC, NC3RS, Wellcome Trust, NIH and EU, and received over £500k of smaller grants and in-kind contributions (equipment, data, expertise) from charities, NHS, and industry, including GSK and AstraZeneca. Systems currently under development include molecular imaging for preclinical research, optical imaging of the human hand for arthritis diagnosis, non-contact optical system for monitoring of wound healing, multispectral ophthalmic imaging for early detection of age-related macular degeneration, and photoacoustic imaging. These projects, some already undergoing clinical evaluation, are prominent examples of the School's *impact pipeline* (1.4).

The Intelligent Robotics lab is housed in a 116m^2 purpose-built space providing state-of-the-art facilities for research in robotics and computer vision. It has a large fleet of mobile and humanoid robot platforms equipped with actuators and sensors for multi-modal input. A sophisticated multi-camera motion capture system is complemented by devices with VR/AR capabilities. Facilities for manipulation research include a custom-built bi-manual half-humanoid torso with a stereo head, 7 DoF arms, and swappable grippers. It serves staff, 25 PDRAs and PhD students, and has been supported by more than £1M in grants from EPSRC and EU, and by contributions in kind from major industrial sponsors including Samsung.

Within the assessment period, **AI research** has benefitted from a large boost to the provision of institutional computing facilities. BEARAI provides high-performance computing on the largest IBM PowerAI cluster in the UK (11 nodes each with 144 cores, 1TB RAM, 4 Nvidia V100 GPUs). Locally, the School has invested £170K in a new ML laboratory hosting 70 workstations with high-performance GPUs and large data storage capacity, and a dedicated GPU cluster for large workloads. Most recently, EPSRC has awarded a grant of £4M (Styles, applied for in the reporting period) to build a *national Tier-2 facility for high-performance computing*, which, with its 2.4 petaflop capability, will be firmly in the upper half of the top 500 list of supercomputers in the world.

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

The arrangements put in place since 2014 to support the expansion and sustainability of our research portfolio have brought significant increases in our external research engagement and impact. In the reporting period, we have collaborated with over 125 organisations from 30+ countries worldwide, working with universities, research institutes, governmental bodies, public sector institutions, and industry. Our portfolio is aligned with EPSRC 'Capability' and 'Challenge' themes, with major contributions to Cyber-Security, ICT (especially theoretical underpinnings of computer science and AI), Mathematical Sciences and Healthcare Technologies. We worked jointly with external partners across other themes including Energy (AI), Engineering (AI, CLS, HCC), Global Uncertainties (Theory, AI, HCC), Digital Economy (HCC), Physical Sciences (AI, CLS) and Environmental Change (AI), further evidencing the breadth of our interdisciplinarity.

4.1   Academic networks and collaborations

This section highlights *academic* research collaborations, with the non-academic sector addressed in 4.2.

Cyber Security is a founding member of the NCSC Research Institute on *Secure Hardware and Embedded Systems*, led by O'Neill (Belfast). We have three active projects within that institute, spanning both 'offensive' and 'constructive' aspects of cybersecurity. We collaborate with leading academics in Cambridge (Watson, Moore), Bristol, and NUS and NTU (Singapore). Our work with Gruss (Graz) and van Bulck, Piessens, Wouters, Gierlichs and Preneel (Leuven) has led to four high-impact papers that have received wide media coverage. The *Du-Vote* voting protocol developed by Ryan in collaboration with Cornell and HP Laboratories is being considered by Smartmatic (US) for deployment in future elections. Work with Boureanu (Surrey) led to security improvements in Apple Pay and MasterCard.

Theory collaborates widely with leading researchers and institutions across the world. We hosted over 20 visiting scholars from 11 countries, including Turing Award winner Dana Scott (Berkeley), and received research presentations from over 100 external speakers. We have received reciprocal invitations to dedicated 'research semesters' at the universities of Princeton, Oslo, Paris, Bonn, Cambridge and others. We co-authored influential papers with Altenkirch, Constable, Cormode, Feldmann, Jacobs, Shulman and Voevodsky, among others. Jung, with colleagues in France, Singapore and China, published in 2018 the solution to the 20-year old *Ho-Zhao problem*. A 2014 paper by Parker and colleagues from Oxford, Brno and IST Austria is the second-highest cited ATVA paper since 2015. His work with Kwiatkowska (Oxford) won the 2016 HVC award for the *most influential work in the last five years in formal verification*. The PRINCESS project in collaboration with DARPA, Harvard and USC generated papers in top venues such as ESORICS and FM. The EU project *Computing with Infinite Data* enabled staff exchanges with 20 partner organisations outside Europe (Korea, Russia, Japan, New Zealand, US, Singapore).

AI has received major funding from the EU through numerous projects, enabling collaboration with partners in over 20 European academic institutions, as well as industry (4.2). We have considerable academic collaborations in UK (Oxford, Cambridge, Imperial, UCL, Manchester), USA (CMU, Princeton, Oxford, Stanford, Yale), China, Singapore, Australia and South Korea. Within the USA, one prominent collaborator is Tim Menzies, former research chair at NASA. These partnerships have resulted in joint publications in top AI journals (*Artificial Intelligence*, *Journal of Machine Learning Research*) and conferences (AAAI, IJCAI, ICML), open software (RT-GENE, one of the most downloaded eye-gaze packages) and co-leading impactful events at major conferences (annual international workshop on eye-gaze at ICCV and ECCV). We have filed patents in EU countries (e.g. on control of drill mining machines in Sweden). Robotics research in collaboration with UK universities, the National Nuclear Laboratory, and government agencies in France has led to the implementation of advanced nuclear decommissioning techniques at Fukushima and Sellafield. Work with Seoul National University has produced novel methods in visual object tracking (published in CVPR'16-18, cited 475+ times).

HCC research is carried out with academic partners across different disciplines including law, psychology, AI, and software engineering. Howes held visiting positions at Michigan and the

Finnish Center for AI, jointly publishing in prestigious outlets (*ACM CHI*, *ACM TOCHI*, *Psychological Review*). Bahsoon co-authored over 25 highly cited papers bridging AI and software engineering. His agenda-setting 2018 CSUR paper *Manifesto for future generation cloud computing*, co-authored with 21 internationally leading scientists from the UK, Europe, Australia and the US, has received over 100 citations to date. Sorge's assistive technology work (ICS-4) has involved extensive international collaborations with academics at universities, charitable bodies and international standards organisations (e.g. W3C). Russell, in collaboration with TU Munich and UP Madrid, delivered a real-time interactive system for stroke patient rehabilitation. Gould's recent paper with colleagues from UCL and Northumbria was submitted as evidence to the UK Parliament and led to a by-invitation seminar for a House of Lords committee examining the effects of the pandemic.

CLS's interdisciplinary research builds on collaborations with clinicians, bioscientists and physical scientists. Pioneering research by Little on the use of digital health technologies in Parkinson's disease led to invited positions at the Oxford Nuffield Department of Clinical Neurosciences and MIT Media Lab. His publications with leading neuroscientists are highly cited in international journals (*Nature Communications*, *Nature Genetics*, *JAMA Neurology*, *Journal of Neurology*). The iPhone app *mPower*, for real-time tracking of Parkinson's disease symptoms, resulted from collaboration with neurologists at the University of Rochester. Dehghani's work with Washington University and Dartmouth College resulted in over 20 publications in high ranking journals (*Biomedical Optics*, *Neurophotonics*, *Physics in Medicine*), including a trailblazing paper on high-density diffuse optical tomography in *Nature Photonics*. Project *BitMap*, involving 10 European partners, developed instruments for non-invasive brain monitoring, resulted in 50+ papers and created standardisation procedures now promoted by the EU Commission. Duan's collaborators include leading researchers from Imperial, Wuhan, Chengdu, and Singapore. Their papers consistently score high citations (4 with 50+ since 2016; 17 with 20+) in journals including *Nature Machine Intelligence*, *IEEE TMI* and *Pattern Recognition*.

4.2   Engagement with users and beneficiaries

Security. We collaborate with major companies (Intel, Infineon, Huawei, IBM, Thales, HP, Samsung) on hardware security, leading to improved designs, attack prevention strategies and security updates, see (3.4) for examples. Research on secure designs for IoT processors is carried out with ARM, Ericsson and Soitec. Ongoing research consultancies and collaborations with Veridify Security, TRL Technology, GCHQ, RITICS, NCSC, Siemens, Mastercard and Visa involve IoT cybersecurity, cloud security, trustworthy voting, secure communications, contactless card security, and supply chain security.

Transport & automotive. National Rail and the Rail Safety and Standards Board, are partners in research for the *European Rail Traffic Management System*. Hyundai sponsors research on in-vehicle driver monitoring. Ford, BMW, Honda and Tata Steel are our collaborators on several projects on engine optimisation and vehicle dynamics. Collaboration with *Inventive Cogs* on vehicle routing has resulted in a patent submission.

Technology. The PRINCESS project *Building Resource Adaptive Software Systems* is funded by DARPA. Airbus is a collaborator on an EPiCS project developing self-aware and self-expressive software architectures. The *Stable Prediction of Defect-Inducing Software Changes* project is partnered with Microsoft, who also provide support for research on cloud verification. Long-standing research collaboration with the Home Office utilises our expertise in speech recognition. Volvo, SAAB and 6 other companies are partners in the Swedish Knowledge Foundation project *Semantic Robots*, with several patents already filed. A 3D imaging technology for bespoke footwear design has been patented and licensed to spin-out 3d Engine Ltd.

Society. Work on enhancing *educational inclusion* by enabling accessible rendering of mathematical expressions on the web, has involved over 20 collaborators from charities, major STEM publishers and standards organisations (ICS-4). Research on speech technologies for

children was sponsored by Disney Research. Work on human decision making is funded by the UK Ministry of Defence.

Healthcare. Leading pharmaceutical companies (GSK, AstraZeneca, UCB) and NPL have supported research on multispectral and chemical imaging for drug discovery. Oxford Nanoimaging and Thermo Fisher Scientific are collaborators in molecular imaging research. HemoPhotonics, PicoQuant Innovations and European hospitals were partners in the EU *BitMap* project developing neuromonitoring devices. The EU *LUCA* project developed a point-of-care, low-cost device for thyroid screening with companies Vermon, Echo Control Medical and HemoPhotonics. Renishaw and Nikon supported development of 3D scanning technologies for stereotactic neurosurgery. UK Biobank, Siemens, Philips and NHS hospitals are partners in the EPSRC *SmartHeart* programme. Within EU *CogWatch*, we work on speech technologies for assisting disability with RGB Medical Devices, Headwise Ltd. and the Stroke Association. Software for remote monitoring and detection of Parkinson's is used in clinical trials across the world and by international pharmaceutical companies (Pfizer, UCB Biopharma). SIAscopy, a non-invasive screening technology for skin lesions, is deployed in 35 countries worldwide, including the *Boots Mole Scanning* service.

4.3 Engagement with wider society

4.3.1 Public engagement

We encourage and support staff and students to engage with schools, local communities, local business and groups of individuals. Examples include Midlands Digital Health Public Debate (Styles), Birmingham Artificial Intelligence Meetup (Jung, Chang), Birmingham Eastside Gallery (Sloman) and numerous 'Pint of Science' talks. Further afield, we took part in British Science Festivals (Little, Ryan), presented multiple local TEDx talks and gave inspirational talks on increasing STEM participation for teachers and visually impaired students (Sorge).

Ghica champions the teaching of abstract mathematical concepts to primary school pupils via blogs and training sessions at the *Association of Teachers of Mathematics*. Final-year undergraduates on the 'Teaching CS in Schools' module visit schools as ambassadors, reaching over 2000 pupils annually and stimulating interest in computer science. All students in our CDTs are registered as STEM ambassadors and co-organise the annual 'Meet the Scientist' event at the Birmingham *Thinktank* Science Museum.

4.3.2 Presence in the media

In the reporting period, the School's research obtained wide media coverage, with examples including newspapers (*Times*, *Independent*, *Guardian*, *Times Higher*), professional journals and magazines (*Nature News*, *Nature Outlook*, *New Scientist*), radio (BBC Radio 4, Radio 5 Live, The World Tonight), television (BBC Newsnight) and the internet (YouTube, Yahoo! News, Wired, ZDNet). During the assessment period *over a quarter* of our academics gained media exposure related to their research.

Two notable examples relate to our research into car security: vulnerabilities in vehicle keyless entry systems of VW Group vehicles resulted in over 130 news items across international media; findings on insecure cryptographic designs of vehicle immobilisers (ICS-1) generated over 150 articles in the international press. Research on new cryptographic protocol testing for banking (ICS-2) had extensive coverage in the business press.

Other topics included electronic voting (BBC Newsnight), railway security (Forbes), medical imaging (*Times*, BBC), Parkinson's disease diagnosis (BBC, *Guardian*, CNN, NPR), AI technology (*Nature News*, BBC, *Daily Mail*) and general science issues (*New Scientist*, *Nature Technology*, *WIRED*).

4.4 Indicators of wider influence, contributions to and recognition by the research base

Fellowships. Over 25% of our academics hold senior status (Fellowships) of professional bodies including IEEE (Yao), BCS (Baber, Beale), RSA (Bahsoon), IMA (Russell), ATI (Kaban, Lehre, Tiňo, Rowe, Sloman, Styles) and Optical Society of America (Dehghani).

Editorships. Half of all academic staff, across all research Themes, are involved in journal editorial work as *Associate Editors and Editors-in-*Chief (17 staff, 29 journals) and *Editorial Boards* members (19 staff, 32 journals).

Conferences. During the assessment period, over 50 keynote or invited plenary talks were delivered by School members. We (co-)chaired nearly 30 international conferences. Almost everyone serves regularly on steering and programme committees for national and international conferences.

Professional bodies. Yao served as president of the IEEE Computational Intelligence Society (2014-15). Four academics chaired or co-chaired IEEE Computational Intelligence Society technical committees: Theoretical Foundations of Bio-inspired Computation (Lehre), Many-Objective Optimisation (Li), High Dimensional Data Analysis (Kaban), Data Mining (Tiňo) and Neural Networks (Tiňo). Baber serves on the REF Panel B12.

Other bodies include: UKCRC (Beale, Barnden, Jung, Ryan, Sloman); W3C (Sorge); Huawei's Security Advisory Board (Ryan); DSTL SERAPIS framework (Baber); Parkinson's UK College of Experts, and DOH Dementia Innovation Unit Citizen Science Platform (Little); GlaxoSmithKline Bioimaging Expertise Network, EPSRC Integrated Bioimaging Network, and Strategic Advisory Board of the Rosalind Franklin Institute (Styles); IEEE CIS Data Mining, and Big Data Analytics Technical Committee (Tiňo); IEEE CIS High Dimensional Data Mining (Kaban); ATI (Rowe).

Grants committees. Ten academics are members of the EPSRC Peer Review College. Outside the UK, colleagues served on grant committees in Austria, Finland, Germany and Ireland. Over half of School members reviewed research proposals for UK organisations, EU ERC, and research councils in 19 countries around the world.

Academic publications. *All* School members contributed to this service to the research community, with some reviewing over 60 papers since 2014.

Journals included core subjects (*Theoretical Computer Science*, *Formal Aspects of Computing*, *IEEE Transactions on Software Engineering*, *Logical Methods in Computer Science*, *Artificial Intelligence*); high-ranking outlets: *Nature*, *IEEE Transactions* (*Neural Networks and Learning Systems*, *Evolutionary Computation*, *Medical Imaging*); and interdisciplinary journals (*Cognitive Science*, *Ergonomics*, *HCI*, *Bioinformatics*, *Biomedical Optics*, *Neuroimaging*, *Symbolic Logic*, *Physica*, *Quantitative Finance*).

Prizes and best paper awards. Both staff and PhD students won best paper awards at conferences across a range of our research Themes. Examples include: Haifa Verification Conference (Parker, 2016), IEEE Congress on Evolutionary Computation (Li, 2014), International Conference on Simulated Evolution and Learning (Li, 2017), International Conference on Intelligent Data Engineering and Automated Learning (Tiňo, 2016), International Symposium on Algorithms and Computation (Lehre, 2014), ACM Human Factors in Computing Systems (Howes, 2014, 2017), International Web for All (Sorge, Lee, 2015), ACM/IEEE Empirical Software Engineering and Measurement (Minku, 2015), IEEE Transactions on Evolutionary Computation Outstanding Paper Awards (Yao, 2016, 2017); IEEE Congress on Evolutionary Computation (Kaban, 2015), Speech and Language Technologies in Education (Russell, 2017), European Conference on Computer Systems (Chothia, 2019), Software Engineering for Adaptive and Self-Managing System (Bahsoon, 2020), Natural Language & Information Systems (Lee, 2020).

Collaborative arrangements for PGR training. The Theory Theme has a long-standing regional collaboration via the *Midlands Graduate School in the Foundations of Computing Science*. EPSRC CDT programmes *PSIBS* and *Sci-Phy* were awarded a University of Birmingham Teaching Academy Award for Educational Enhancement & Innovation. School members run numerous international summer schools and training workshops across all the Themes: 'Naturalistic Decision Making', 'Machine Learning', 'Software Engineering', 'Denotational Semantics', 'Programming Languages', 'Optics & Photonics' and more than 10 others. EU Marie Curie programmes funded ITN *BitMap*, *ECOLE* and *RISE* with contribution to the School of over £300,000.

Other indicators of influence and recognition. Yao was awarded the 2020 IEEE Frank Rosenblatt Award and IEEE Computational Intelligence Society 2017 Meritorious Service Award. He is a Distinguished Lecturer of the IEEE Computational Intelligence Society, and is ranked 6th in the UK G2R and 177th in the World G2R. Sloman is the 2020 American Philosophical Association Barwise Prize winner. Baber delivered the 2014 Chartered Institute of Ergonomics and Human Factors Donald Broadbent Lecture. Howes was a 2016 Marshall Weinberg Fellow at the University of Michigan. Long-term visiting positions were held at USTC, Finnish Center for AI, CMU, Israeli Center for Algorithms, and Universities of Michigan, Melbourne, and Illinois. Escardó was invited to visit a number of prominent research institutes including Newton Institute for Mathematical Sciences, Institute Henri Poincaré, Norwegian Center for Advanced Study and Hausdorff Research Institute for Mathematics (Bonn).