Institution: University of Warwick

Unit of Assessment: B11 Computer Science and Informatics

1. Unit context and structure, research and impact strategy

This submission is led by the Department of Computer Science in the Faculty of Science, Engineering and Medicine (FSEM), and includes two researchers from the Centre for Interdisciplinary Methodologies (CIM) in the Faculty of Social Sciences, and one researcher from the Institute for Global Sustainable Development (IGSD) in the School for Cross-Faculty Studies. An overview of the Faculties and Departments of the University of Warwick is in **REF5a-1.6**. Our staff base comprises 46 research and teaching academics, 38 postdoctoral researchers, 12 teaching-focused staff and two software engineers, supported by 16 administrators and five technicians.

Our core strengths include: advancing knowledge in algorithms, logic, data science, high performance computing and artificial intelligence; solving challenges in the areas of nuclear safety, citizens' participation in public life, intelligent vehicles, law enforcement, and personalised healthcare; and contributing to the economic development and global competitiveness of the UK in high tech industry. Our outputs and impact case studies illustrate these core strengths and reflect the University's overall vision of "Excellence with Purpose" (**REF5a-2.1**).

Computer Science at Warwick is renowned internationally for the quality of its research, and was recognised nationally as 1st for outputs and 2nd for impact in the REF 2014 rankings. We compete globally to recruit the best researchers and PhD students, creating an inclusive, outward-looking and sustainable research environment. Research is central to our culture: our teaching is research-led, and teaching-focused staff are members of research themes.

Research themes

Computer Science research at Warwick is organised into four themes: Theory and Foundations; Data Science, Systems and Security; Artificial Intelligence and Human-Centred Computing; and Applied Computing. Through this structure, we can ensure critical mass in key areas, and devolve decision-making and resources in matters of research. This has proved beneficial in: mentoring and developing PhD students, postdoctoral researchers and junior academics; identifying funding opportunities and winning grants; and integrating with wider research taking place cross-campus, via interdisciplinary research centres (**REF5a-2.9.4**), and Global Research Priorities (GRPs – **REF5a-2.9.1**). The organisation is depicted in *Figure 1*, with further details in *Table 1*.

Theory and Foundations (ThFo) researchers work on hard problems in the fundamentals and applications of algorithms, computational complexity, discrete mathematics, logic and game theory, operating at the highest level of the international research community in theoretical computer science. Led by *Czumaj* with deputy *Lazić*, this theme is staffed by three Professors, five Readers and Associate Professors, five Assistant Professors, and one Senior Research Fellow. *Czumaj* heads the interdisciplinary DIMAP centre (*Table 1*).
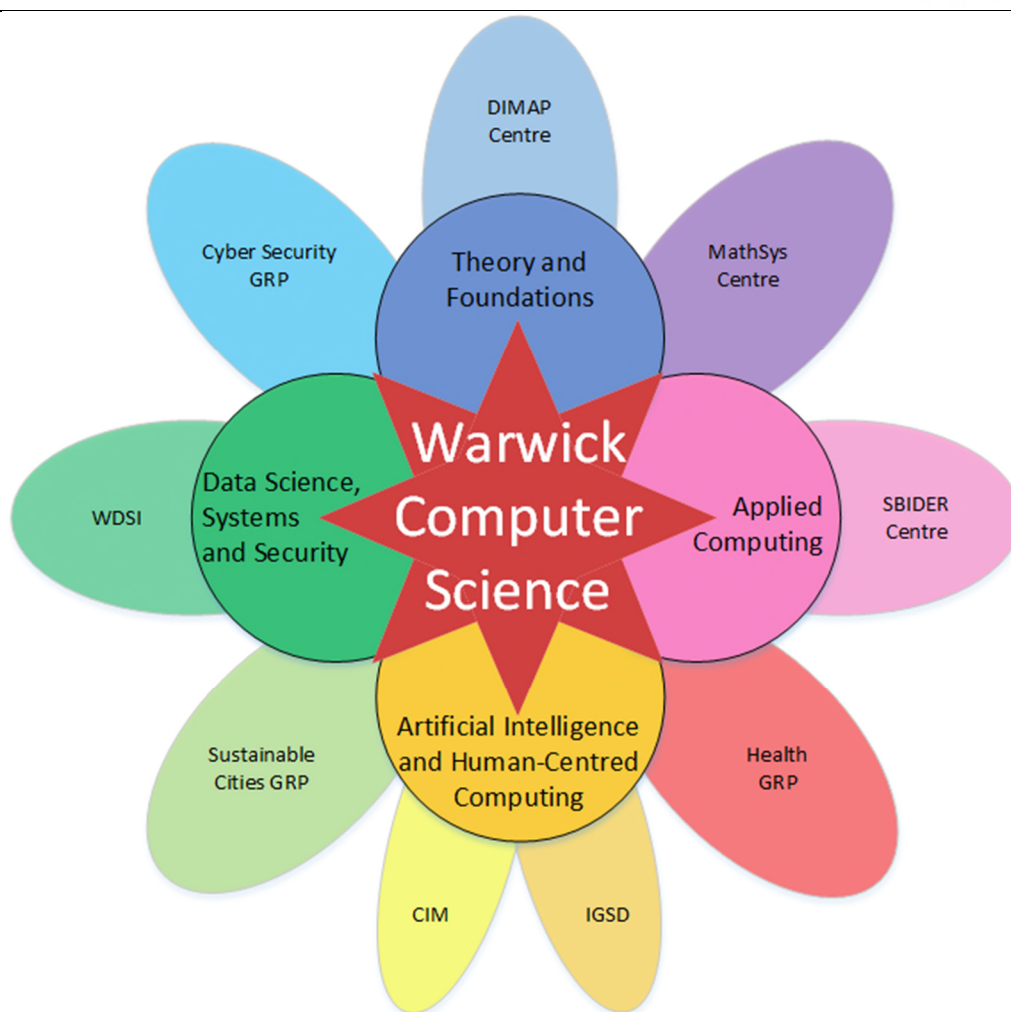
Figure 1. Research themes, interdisciplinary research centres, and GRPs

DIMAP	Discrete Mathematics and Its Applications
WDSI	Warwick Data Science Institute
CIM	Centre for Interdisciplinary Methodologies
IGSD	Institute for Global Sustainable Development
SBIDER	Systems Biology and Infectious Disease Epidemiology Research
MathSys	Mathematics for Real-World Systems

Table 1. Abbreviations occurring in Figure 1

During this REF period, the theme has been expanded by seven strategic appointments in combinatorial optimisation and dynamic algorithms (*Bhattacharya*, *Sridharan*), complexity, cryptography and quantum computing (*Gur*, *Oliveira*), and discrete mathematics and logic (*Chistikov*, *Efthymiou*, *Mütze*). Members have brought in two ERC grants, a UKRI FLF, a Royal Society URF and seven EPSRC grants; they have published 26 papers at the most prestigious conferences in the field, FOCS and STOC, including a Best Paper Award at STOC 2019; and have been elected President of the European Association for Theoretical Computer Science (*Czumaj*) and Fellow of the American Mathematical Society (*Král'*). The theme contributed 31 outputs to this REF.

Data Science, Systems and Security (DSSS) researchers develop new techniques for data management and analytics, data mining, statistical machine learning, high performance computing, networks and performance evaluation, and cyber security. They tackle practical problems in areas including sustainable cities, aerospace engineering, nuclear safety, secure communication, and electronic voting. Led by *Triantafillou* with deputy *Hao*, this theme is staffed by four Professors, six Readers and Associate Professors, two Assistant Professors, and one teaching-focused senior colleague. *Cormode* is Warwick's ATI University Lead (**page 5**) and coordinates WDSI (*Table 1*). *Ferhatosmanoglu* directs the EPSRC CDT in Urban Science.

The theme has been strengthened by seven strategic appointments in: data science and systems (*Ferhatosmanoglu*, *Triantafillou*), data mining and statistical machine learning (*Damoulas*, *Yu*), high performance computing and performance evaluation (*Mudalige*, *Mukhopadhyay*), and cyber security (*Hao*). Members have won significant prestigious funding including two ERC grants, an ERC Proof of Concept grant, a Royal Society Industry Fellowship, and ~£2M worth of high-profile partnership projects with the Atomic Weapons Establishment (AWE), Huawei and Rolls Royce. *Cormode* was awarded the 2017 Adams Prize by the Cambridge Faculty of Mathematics. The theme contributed 22 outputs to this REF.

Artificial Intelligence and Human-Centred Computing (AIHCC) researchers focus on artificial intelligence in the engineered and social worlds, using discoveries in multiagent systems, ubiquitous computing, natural language processing and visualisation to solve real-life challenges in areas such as intelligent vehicles, cyber-physical systems, mental health, rumour verification, and geography and ecology. Led by *Procter* with deputy *Griffiths*, this theme is staffed by four Professors, six Readers and Associate Professors, one Assistant Professor, and three teaching-focused senior colleagues. *Porto de Albuquerque* heads IGSD (*Table 1*), co-heads the Warwick Institute for the Science of Cities, and is the Warwick lead of the international Centre for Urban Science and Progress (CUSP) in London. *McInerny* and *Turkay* are members of CIM (*Table 1*).

The theme has been strengthened by seven strategic appointments in game theory and autonomous agents (*Tran-Thanh*, *Turrini*), ubiquitous computing (*Wen*), text mining and natural language processing (*Y He*), digital geography and geographic information science (*Porto de Albuquerque*), and data and information visualisation (*McInerny*, *Turkay*). Research has been supported by a portfolio of funding including a Royal Society Industry Fellowship, a £2M EPSRC partnership project with Jaguar Land Rover, a £1.2M Turing AI Fellowship, and ~£2.5M from UKRI GCRF, ESRC and NIHR. The theme contributed 18 outputs to this REF.

Applied Computing (AppCo) researchers develop new methods in image and video analysis, machine learning, bioinformatics and computational neuroscience, seeking alignment with applications to people identification, early cancer detection, personalised healthcare, cell biology, and psychiatric and neurological treatments. Led by *Rajpoot* with deputy *Timofeeva*, this theme is staffed by six Professors, two Readers and Associate Professors, three Assistant Professors, and one teaching-focused senior colleague. Members have leadership roles in the MathSys and SBIDER centres (*Table 1*). *Rajpoot* also heads the newly formed interdisciplinary Tissue Image Analytics centre, linked to the Health GRP.

The theme has been expanded by four strategic appointments in applied machine learning and bioinformatics (*Bretschneider*, *Minhas*, *Raza*), and signal and information processing (*Guha*). Members have brought in a £2.3M Innovate UK project on computational pathology, a £1.4M EU H2020 project on multimedia forensics, and a number of BBSRC, MRC, NHS and NIHR grants. The theme contributed 21 outputs to this REF.

Strategy for research and impact

Early in this REF period, both the Department and the University underwent a strategy renewal, initiating a period of investment and growth. Our refreshed strategy, from 2016, encompasses and builds on the objectives set out in our submission to REF 2014, of (1) pursuing interdisciplinary research in order to benefit society, (2) developing new computing science techniques and methods of application, and (3) engaging in knowledge transfer with government and industry. It expresses an increased ambition, following the rapid advances we made in the period 2014-16. CIM (**REF5a-2.9.4**) and IGSD (**REF5a-2.9.3**) were created around the same time (in 2012 and 2014 respectively), extending the reach of Computer Science across the University.

Research and impact in the Department are overseen by the Research Strategy Committee, which is chaired by the Director of Research, and includes the Director of Impact, the Heads and Deputy Heads of the research themes, a representative of Early Career Researchers (ECRs), Warwick's ATI University Lead (**page 5**), and senior members of Research and Impact Services (R&IS – **REF5a-1.7**). Equality, Diversity and Inclusion is overseen by the Athena SWAN Working Group, our postgraduate research by the Postgraduate Research Committee, and our links with industry by the Industrial Advisory Board. All four committees report to the Departmental Steering Committee. Integration and alignment with University strategy are ensured through the participation of the Head of Department and the Director of Research in the FSEM Research and Innovation Forum. This structure is depicted in *Figure 2*.
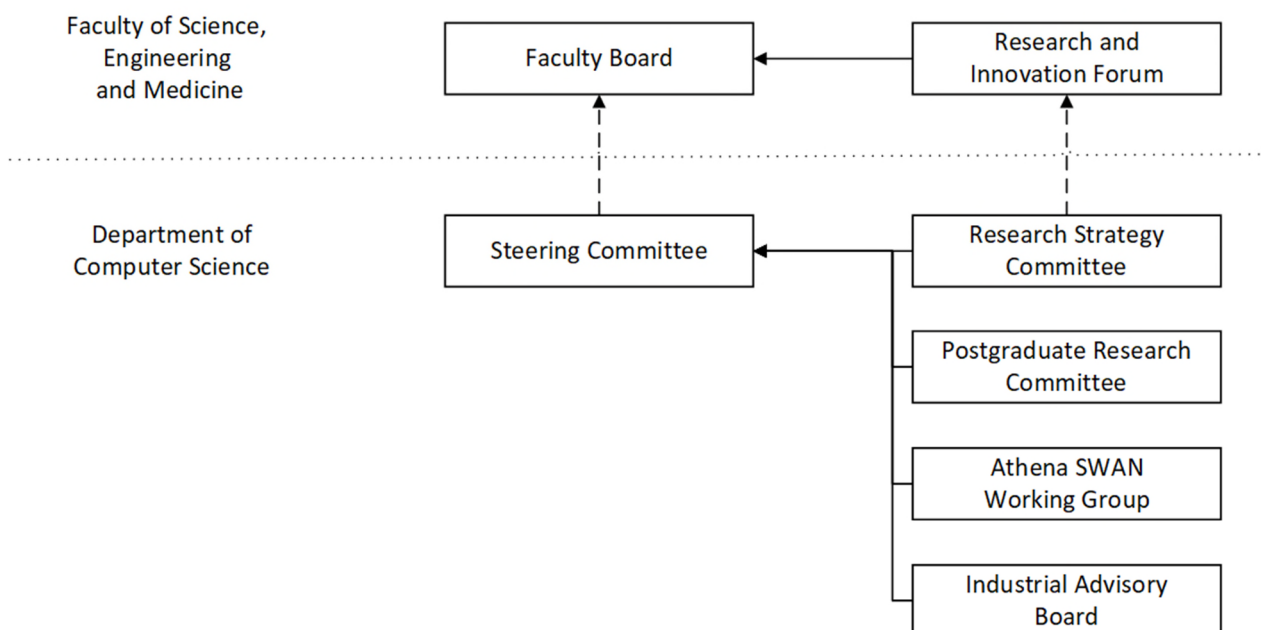

Figure 2. Committees overseeing research and impact

Our strategy is articulated by and taken forward through the seven work strands below, which align with the University research strategy (**REF5a-2.2**). By implementing it, we have won **£15.8M** in research income during this REF period, compared with **£6.1M** during the previous one. Part of this increase is linked to expansion (from **24.4 FTE** staff submitted in REF 2014 to **41.6 FTE** in REF 2021), however our performance in measures such as annual research income and doctoral and postdoctoral populations, has outstripped this growth in staff (*Figure 3*).

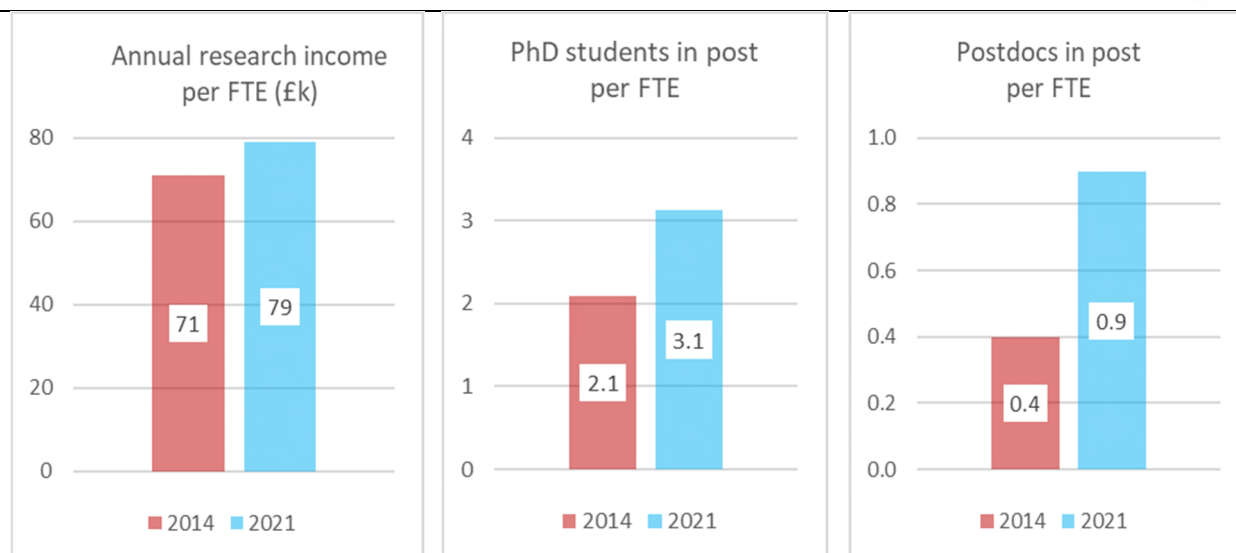| Annual research income per FTE (£k)	PhD students in post per FTE	Postdocs in post per FTE
71 / 79 (2014 / 2021)	2.1 / 3.1 (2014 / 2021)	0.4 / 0.9 (2014 / 2021)

Figure 3. Growth per FTE staff from REF 2014 to REF 2021: research income in the last year of the period, and PhD students and postdocs in post on census date

Work Strand I. *Support, foster and showcase the talent and ambition of all our researchers.*

We attract, foster and retain academics by means of reduced workloads for ECRs, a sabbatical policy, a transparent promotion scheme, and rewards for senior staff that are commensurate with the Oxford-Cambridge-London triangle. We encourage and support staff, via our workload model, to pursue fellowships, awards, and leadership roles. We also celebrate their achievements, which in this REF period include: 14 fellowships from EPSRC, ERC, Leverhulme, Royal Society, Turing AI Fellow, Turing Research Fellow and UKRI Future Leaders Fellow schemes; four Wolfson Research Merit Awards; Presidency of the European Association for Theoretical Computer Science (*Czumaj*); and Adams (*Cormode*), Shimon Even (*Gur*) and Philip Leverhulme (*Král'*) prizes.

Work Strand II. *Undertake world-leading research at the forefront of knowledge.*

During this REF period, our Departmental and research theme seminar series, our workshops and our visitors programme have featured talks by recipients of the Turing Award, the Nevanlinna Prize and the Gödel Prize. The worldwide reach of such programmes, together with our support for researchers to attend leading conferences, embeds an international perspective in the Unit. Regular reading groups within the themes, where senior and junior members meet to discuss latest international advances in their fields, further underpin our culture of excellence. Ten out of 92 outputs in this REF submission won best paper awards, demonstrating the success of this approach.

Work Strand III. *Spearhead research with relevance for impact and innovation.*

Our theme structure facilitates a pipeline from theoretical advances through to impact and innovation. Key to this pipeline is our relationship with the Alan Turing Institute (ATI), of which Warwick is one of five founding partners. The ATI links theoretical and applied researchers in all four themes with real-world problems and data. We encourage and enable colleagues to serve on its Board of Trustees (*Jarvis*), as ATI University Lead (*Cormode*), Deputy Programme Director

(*Damoulas*) and Interest Group Organisers (*Liakata*, *Procter*, *Triantafillou*). Twelve of our academics have held ATI Fellowships.

Work Strand IV. *Cultivate world-class interdisciplinary research communities.*

We foster interdisciplinarity because we recognise that global challenges cannot be tackled by research in Computer Science alone. We facilitate joint academic appointments, and we encourage and enable staff to lead in the University's interdisciplinary research centres and GRPs, e.g. DIMAP (*Czumaj*, *Král'*), MathSys (*Bretschneider*, *Timofeeva*), SBIDER (*Bretschneider*), Tissue Image Analytics (*Rajpoot*), Cyber Security (*Wen*) and the Warwick Institute for the Science of Cities (*Jarvis*, *Porto de Albuquerque, Procter*). This approach has helped ensure an impact pipeline, including future case studies. Of these, the most advanced are based around the recovery of high streets during and after the COVID-19 pandemic (*Damoulas*, ATI), electronic voting (*Hao*, Cyber Security GRP), intelligent vehicles (*Griffiths*, with Psychology and Warwick Business School), the management of flooding in Brazil (*Porto de Albuquerque*, IGSD), and the deployment of computational pathology in the NHS (*Rajpoot*, Tissue Image Analytics centre).

Work Strand V. *Pioneer state-of-the-art accessible research infrastructure.*

We take pride in our technical and organisational research infrastructure, at the heart of which is our specialist team of five technicians. We work with the University to develop the Technicians' Commitment (**REF5a-3.3**), which provides transparent opportunities to progress to professorial-grade roles, and supports professional registration and appropriate credit for authorship on research outputs. In order to pool technical expertise, extend access to equipment, and maximise the utilisation of facilities such as cooled server rooms, our senior technicians collaborate with colleagues in the Scientific Computing Research Technology Platform (RTP – **REF5a-4.3**), central IT Services, and other University departments.

Work Strand VI. *Communicate our research to provide leadership and influence in the global knowledge economy.*

We work with the University Press Office in order to disseminate our research to global audiences. Recent high-profile stories include the use of machine learning for the discovery of exoplanets (*Damoulas*) and a breakthrough in understanding the spin states of quantum-entangled particles (*Chistikov* and *Paterson*). The integration of teaching-focused colleagues into our research environment has allowed us to engage with a wide range of audiences (**page 22**), including the general public.

Work Strand VII. *Build an income and partnership platform to sustain and grow our world-leading activity.*

Securing external funding is a key component of our research strategy. Research themes hold termly meetings to identify funding opportunities, and run internal peer reviews of proposals. In the period 2019-2020 alone, our Assistant Professors won £900k from the UKRI FLF scheme (*Gur*), £620k in Royal Society URF funding (*Oliveira*), and ~£600k in EPSRC grants (*Bhattacharya*, *Oliveira*, *Sridharan*). Our administrative staff work closely with central University colleagues to ensure the successful delivery of projects and nurture relationships with funders. Our technicians run secure laboratory and computing facilities which sustain research programmes requiring high levels of confidentiality and security, including £560k of postdoc and

PhD work with AWE (**DSSS** theme), and £3.8M for the Cooperative Car (**page 20**) and ASiMoV (**page 20**) projects, during this REF period.

Impact case studies

Impact of high performance computing (HPC) research on the UK and international HPC industry – This case study is centred on the growth and achievements of Allinea Software Ltd, a spin-out based on and nurtured through HPC research by the **DSSS** theme.

High performance computing for national nuclear security – Resulting from partnerships between the **DSSS** and the UK AWE and the US National Nuclear Security Administration, this case study captures the economic and national security impact of HPC research.

Impact of image analysis research on fingerprint biometrics and multimedia device fingerprinting – Underpinned by image analysis research in the **AppCo** theme, this case study reports economic and societal impacts of the spin-out Warwick Warp Ltd and the company Biosite Systems Ltd, the patented Forensic Image Analyser (sold by Forensic Pathways Ltd) and a licensed Sensor Pattern Noise tool.

Impact of user-generated content analytics on national broadcast news and independent fact checking – Centred on the BBC Radio "Five Live Hit List" and the Full Fact "Live" software, this case study reports the impact on society, culture and public policy of novel user-generated content analytics work by the **AIHCC** theme.

Impact described in the second case study was supported by a £10k Warwick Impact Leave Scheme award (*Jarvis*), and in the fourth by a £46k Warwick EPSRC IAA award (*Procter*) – see **REF5a-2.7**.

Openness and integrity

Our approach to integrity runs through all work strands, underpinning our research strategy. We routinely invite scrutiny and collaboration by working openly. This also supports our impact agenda, since we achieve significant uptake by non-academic users by engaging with open source initiatives.

Research Dissemination – As well as depositing all research outputs in the Warwick Research Archive Portal (WRAP – **REF5a-2.10**), we commonly release pre-prints in widely used external public archives (e.g. arXiv, bioRxiv, Cryptology ePrint Archive). We also push for books to be accessible openly, such as *Hao's* CRC Press volume[1] and *Cormode's* CUP book[2]. We make data open wherever possible, e.g. the Warwick-JLR Driver Monitoring Dataset and the Road Classification Dataset[3], the Gland Segmentation Challenge Contest at MICCAI 2015[4], and the HER2 Scoring Contest in conjunction with Nottingham Pathology 2016[5]. *Hao's* open-source implementation for the J-PAKE protocol formed the basis for the subsequent industrial implementation of J-PAKE by ARM, Google, Mozilla, Openssl etc. We have initiated widely-read

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[1] https://www.realworldevoting.com/
[2] http://dimacs.rutgers.edu/~graham/ssbd.html
[3] https://www.dcs.warwick.ac.uk/dmd
[4] https://warwick.ac.uk/fac/sci/dcs/research/tia/glascontest
[5] https://warwick.ac.uk/fac/sci/dcs/research/tia/her2contest

Wikipedia articles about our research results, e.g. av-net, ov-net, YAK, J-PAKE, and contributed to open standards such as IETF RFCs, e.g. RRC 8235 and RFC 8236, based on our research results. We participate in open competitions, for example the computational pathology Multi-organ Nuclei Segmentation and Classification Challenge 2020, which our Tissue Image Analytics centre won (*Rajpoot*).

Reproducibility – Chairing the reproducibility committee of the Proceedings of Very Large Databases since 2018, and contributing to the similar effort within the ACM SIG on Management of Data since 2015, *Triantafillou* has instigated changes to international peer review processes to make code and datasets available for scrutiny. As Program Co-Chair of EMNLP 2020, *Y He* introduced a reproducibility checklist to the paper submission process, for the first time in the history of NLP conferences. *Damoulas* won "Most Reproducible Paper of ACM SIGMOD 2016", and *Damoulas* and *Liakata* won two out of three "Turing Reproducible Research Champion" awards in 2018.

Research integrity – The legal and ethical underpinning of our research is ensured through the University's ethics review processes and compliance mechanisms, and the training that all researchers undergo as part of their induction such as the Epigeum research integrity training (**REF5a-2.11**). Beyond these institutional requirements, Computer Science embeds a culture of research integrity by including ethics experts as key members of our project teams wherever relevant. For example, several colleagues in the Department work with *Professor Tom Sorell*, Head of the Interdisciplinary Ethics Research Group in the Department of Politics and International Studies. *Sorell* is a member of the Tissue Image Analytics centre (**page 20**) and chaired the ethics review board for the IDENTITY project (**page 20**).

Vision towards 2030

We will continue pursuing the seven work strands presented above, inspired by the six strategic priorities of the University (**REF5a-2.1**), which are highlighted in the following vision.

Computer Science at Warwick stands on the threshold of an exciting new era. Our trajectory since the RAE 2008 is clear and consistent. Having always had a global outlook, we have now become more integrated and collaborative across the University; we have increased the size and quality of our research base according to a number of key measures; and we have built new partnerships leading to significant impact. Other disciplines are rapidly recognising the value that Computer Science can bring to their own areas of enquiry, e.g. using data science and artificial intelligence to make **transformative interdisciplinary advances**. Indeed, Computer Science is regarded as key to the University's STEM Grand Challenge (**REF5a-4.2**).

Over the next ten years, we will seize the opportunity to open up **innovative areas of discovery** such as quantum cryptography and computing, robots as experimental scientists, and smart factories, working side by side with colleagues in Physics, Chemistry and Engineering in the new £300M+ interdisciplinary Science Precinct. Building also on our established and emerging areas of **disciplinary and interdisciplinary excellence**, we will enhance collaborations, especially with Mathematics, Statistics, Life Sciences, Medicine, CIM and IGSD, strengthening research directions in algorithms, explainable artificial intelligence, data science, cyber security, natural language processing, computational social science, agent technology, image and video processing, computational pathology and bioinformatics. Spearheading and supporting the institutional strategies, we expect to grow further by at least 30% in this period.

We will nurture existing **partnerships** such as those with AWE and Rolls Royce, and we will realise the benefits of activities that are currently at an earlier stage of development, leading to impact of **global reach and significance** in urban analytics, flood management, electronic voting, intelligent vehicles, and the diagnosis and personalised treatment of cancer.

By 2030, with our research embedded across the institution, we envisage Computer Science at Warwick continuing to lead the way nationally, extending our world class reputation to new fields. We will continue to foster our ethos of **excellence with impact** through an open, egalitarian and supportive research environment, in which ideas flow bottom-up, resources are devolved, and success is rewarded.

2. People

Our research and impact strategy relies on supporting and rewarding people who make up Computer Science at Warwick, and we are committed to implementing the principles of the revised Concordat to Support the Career Development of Researchers, of which the University is a signatory.

Equality, diversity and inclusion

The Department was re-awarded an Athena SWAN Bronze in 2019, and we are committed to an ambitious action plan to take us to Silver in 2024. The Head of Department is a member of the institutional Athena SWAN Self-Assessment Team. We embrace the Race Equality Charter, which provides a framework for identifying and overcoming systemic and cultural barriers for minority ethnic staff and students, and improving the representation, progression and success of such staff and students. We promote the Dignity at Warwick policy to ensure that all members of the Department are treated fairly and with dignity and respect, and that bullying and harassment are not tolerated.

We strive to ensure equality of opportunity at all career stages, from student admissions and outcomes, through to staff recruitment and promotion. Meetings and research seminars take place in family-friendly hours, and support is offered for childcare at conference attendance. We ensure full accessibility for disabled colleagues, including research students, for Departmental activities. We support flexible retirement and provide office space for emeritus colleagues, who are integrated into research themes and participate in externally-funded research.

Our embedding of ED&I is reflected in the composition of the committees overseeing research and impact (*Figure 2*). Steering Committee consists of five men and four women, or seven academic and two support staff; Research Strategy Committee is chaired by a woman, and consists of nine senior and two junior staff; and Postgraduate Research Committee includes five senior and three junior staff.

Supporting wellbeing

We promote wellbeing through University-wide provision such as The Big White Wall, a Digital Mental Health Service, providing staff and students with support at all times. We publicise our Employee Assistance Programme (EAP), which is free of charge to staff and PhD students.

During this REF period, the Department has invested in social facilities including refurbishing staff and student common rooms, furnishing spaces for break-time activities, and purchasing board games and a bean-to-cup coffee machine. Twice a week, we have coffee breaks with free refreshments, which integrate academics, support staff, and PhD students. Every year, we typically hold three all-staff meetings preceded by shared lunches, two away days focused on strategic topics, a Christmas lunch, and a summer barbecue followed by outdoor games.

To maintain cohesion and provide support during the COVID-19 pandemic, we organised twice-weekly online coffee and tea breaks, social gatherings using a virtual environment, and an online team for communication and advice among staff and PhD students when working on campus. We also assisted members in need with provision of office-standard furniture in their homes, and equipment for effective remote working.

These efforts are bearing fruit: in the past three biannual staff engagement surveys, the engagement score for Computer Science has been on average 5% higher than across the University.

Staffing policy and recruitment approach

During this REF period, we have refreshed our staffing strategy and policies in order to address the rapidly developing nature of our subject, including new interactions with other disciplines and novel application domains, and a rapidly shifting funding landscape. Our approach takes into account the ambitious growth plan articulated in our strategy renewal in 2016, and addresses the fierce competition for excellent staff, both with other universities nationally and internationally, and with other employers of highly skilled computer scientists. We recognise that, historically, our staff base has been less diverse than sector benchmarks, and we have sought to redress this by embedding ED&I in every aspect of our strategy.

Our staffing policy has two pillars, which together secure the vitality and sustainability of our research environment. The first of these focuses directly on our researchers and ensures that they are integrated into research themes which cover the discipline as broadly as possible while preserving research excellence, and which provide fruitful platforms for engaging with emerging interdisciplinary research agendas. The themes are nurtured so that they (1) facilitate sustainable career pathways and effective mentoring schemes for their members, (2) are well resourced by external income and internal investment, and (3) are sufficiently cohesive to support vibrant programmes of reading groups, seminars, workshops and visitors. In doing so, we recruit early career researchers who are building an international profile through fixed-term postdoctoral project work, and research and teaching academics to whom we offer indefinite contracts in order to provide security for the independent pursuit of excellence.

The second pillar focuses on support for our researchers. We ensure that staff who undertake research are complemented by a smaller number of selected teaching-focused staff. In this REF period, we have boosted the research themes by five senior and nine junior teaching-focused colleagues, through a mixture of recruitment and internal promotion. This has helped us maintain teaching excellence in the context of higher student numbers, while preserving research capacity. We benefit from a team of specialised technicians on indefinite contracts, who have an appropriate mix of hardware and systems expertise, and a team of skilled administrators with a range of expertise from research finance to project management to doctoral training, who have indefinite contracts unless directly employed on a project. The increased scale and complexity of operations in the Department, including collaborative working with colleagues across the University and the

sector, has been addressed by introducing more structure and capacity into professional support teams, investing in training and development, and recognising the skills of senior staff through re-grading.

The level and focus of new academic positions are decided by the Steering Committee, in line with Departmental and University research strategies. Our recruitment processes for academic staff, postdoctoral researchers and doctoral students are merit-based, with global reach. The overarching criterion is excellence, with flexibility in how it is demonstrated over the research and impact spectrum. All posts are widely advertised, taking advantage of social media and networks such as Women in Machine Learning. Advertisements encourage candidates from underrepresented groups to apply, using inclusive wording and highlighting our flexible and part-time working policies. All Departmental researchers at the same grade or higher are invited to participate in shortlisting. Training in Unconscious Bias and GDPR is a prerequisite for this, and panel members are also trained in Effective Recruitment and Selection. Panel membership is rotated across research themes, and the "all-male panel" is banned. The selection process has been expanded in this REF period to include teaching and research presentations, and more one-to-one meetings with a cross section of staff. Successful candidates are offered an internationally competitive salary, plus family relocation expenses.

We facilitate joint appointments, of which we currently have two with the Department of Statistics and one with Mathematics. Three colleagues submitted in this Unit are based in CIM and IGSD.

Outcomes of the staffing policy

We have increased the breadth and connectedness of our research themes by expanding the three groupings with which we started this REF period into four themes. Specifically, "Systems and Software" has been superseded by the **DSSS** and **AIHCC** research themes. This has been achieved through a mixture of senior recruitment (*Ferhatosmanoglu*, *Hao*, *Triantafillou* – all **DSSS**, and *Y He* – **AIHCC**) and the integration of a senior academic from IGSD (*Porto de Albuquerque* – **AIHCC**). We have supported collaboration, and the pipeline from discovery to impact, by expanding into cryptography through the appointment of *Hao*, and *Gur* (**ThFo**). This development has resulted in a major grant and feeds into a future impact case study about electronic voting. The appointments of *Minhas* and *Raza* (both **AppCo**) have boosted our interdisciplinary work with Warwick Medical School and University Hospitals Coventry and Warwickshire, resulting in the establishment of the Tissue Image Analytics centre and also leading to a future impact case study. The appointment of *Mudalige* (**DSSS**) has been key in sustaining the nuclear security impact case study.

During this REF period, 14 out of 25 appointments have been at Assistant Professor level, spread across the themes, ensuring an excellent pool of junior staff for succession planning. 24 appointments have been from outside Warwick and 11 from outside the UK, showing that we are able to compete globally for the best candidates and attract them to Warwick – previous affiliations include Berkeley, EPFL, Goethe Frankfurt, ICR London, IIT Kanpur, Imperial, NYU, Oxford, TU Berlin, TU Vienna. During this REF period, we have increased the number of female professors from zero to three (one of whom is teaching-focused), evidencing an approach to staffing that encourages diversity and rewards excellence wherever it is found.

Support for junior academics and postdoctoral researchers

Junior academics receive a competitive package of support from the Department and their research theme, for equipment, travel and hosting visitors. They have an academic mentor in the Department, normally the head of their research theme, with whom they have termly meetings to review progress and obtain advice. They benefit from reduced teaching and administrative loads, starting at 50% of standard and increasing gradually over their period of probation, which is normally for five years and during which they have annual probationary meetings with the Head of Department. They have opportunities to supervise PhD students, and contribute to the life of the Department through acting as deputies to leadership roles (e.g. Director of Student Experience).

Postdocs have regular meetings with their PI. Where a researcher is recruited on a more junior grade because they do not yet hold a PhD, they are upgraded automatically on conferral of the PhD. They are eligible for further promotion based on merit. Postdocs benefit from tailored development courses from Warwick's staff development unit, Organisational Development, and careers advice through a University forum for research-active staff. For those who are aiming for an academic career, the Department optionally provides flexible teaching opportunities agreed with their PI, where this is compatible with their funding. In this REF period, our postdocs have progressed to academic positions at institutions including Universitat Autonoma de Barcelona, Birmingham, Bristol, City, Derby, Goldsmiths, Krakow, Liverpool, Universidad Panamericana Mexico City, New South Wales, Queen Mary, Ulm, Victoria, Warsaw, York, and to industrial appointments at companies including Creavo Medical Technologies, Huawei, Majestic12, NATS, Oxbotica, and Veridium.

Staff development and promotion

All new academics and postdocs receive a bespoke induction, covering key aspects of working at Warwick such as local financial and IT regulations, with informal sessions on teaching and personal tutoring in the Department. They are allocated a mentor within the Department (available to all colleagues, including senior staff). We encourage uptake of the Warwick Leadership Programme, and for female colleagues, the national Aurora programme run by Advance HE. We work within the University's Personal Development Review framework to offer structured career development support annually for all colleagues.

Promotion for academics is on the basis of merit, via a transparent set of criteria, and is available equally for part-time and full-time staff. Women and other underrepresented groups are particularly encouraged to apply, and Assistant Professors are supported to apply for early completion of probation and consequent promotion to Associate Professor.

Out of 46 research and teaching academics in this submission, eight have been promoted to Associate Professor, five to Reader, and six to Professor during the past REF period. Together with our successful recruitment and low attrition rate, the profile of our research and teaching staff shows steady growth, alongside maintaining a balanced seniority profile (*Figure 4*).
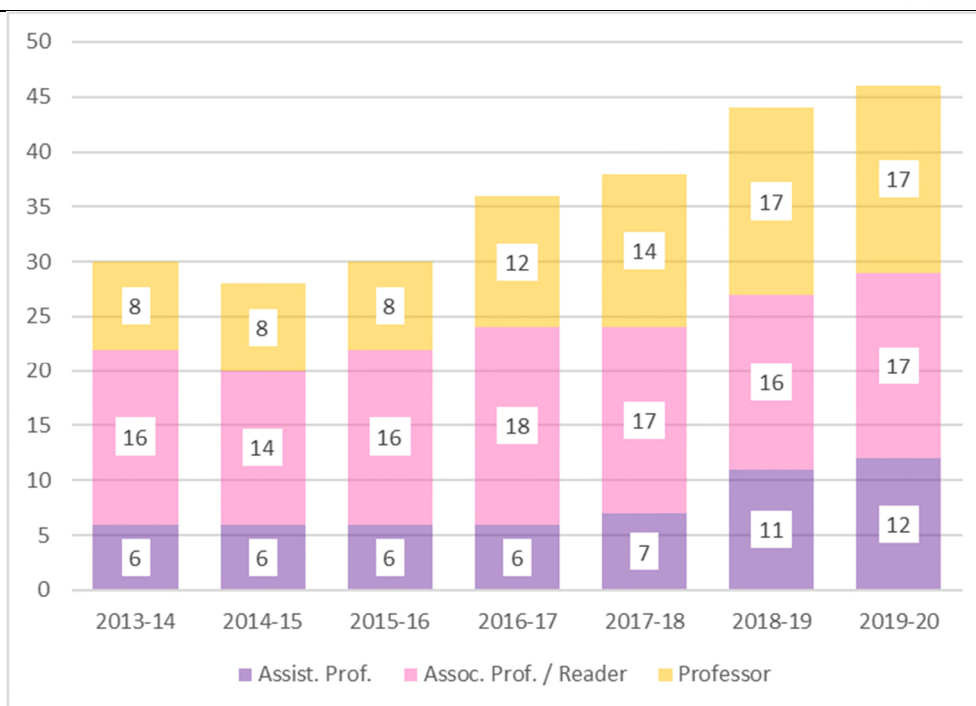
Figure 4. Composition of research and teaching academic staff

Workload, leave and flexible working

Our approach to workload is designed to ring-fence space for research and impact activities, while ensuring that teaching and other activities that contribute to the life of our community are appropriately resourced. We operate a flexible workload model which takes into account research, teaching, impact/engagement, and collegiality/management.   Colleagues receive credit for interdisciplinary teaching and for supervision that crosses departmental boundaries. Staff on full fellowships are relieved of all standard duties, apart from teaching approximately one half module of advanced courses, in order to help disseminate their research and build their groups.

All academic staff are eligible for one year of sabbatical leave for every six years of service. We also facilitate leave to accept a research award (e.g. *Fijalkow* at University of Bordeaux, *Rajpoot* at Qatar University), part-time contracts to allow colleagues to take up appointments in industry (e.g.: *Feng*, Institute of Science and Technology for Brain-Inspired Intelligence at Fudan; *Wen*, Samsung AI Research Centre at Cambridge), and external consultancies and directorships (working with 13 start-ups, corporations and government agencies in this REF period). We support academics to apply for impact leave, and to bid for awards from the Higher Education Innovation Fund and the Impact Acceleration Accounts (cf. **page 7**). We encourage academics returning from parental leave to take up the Warwick Academic Returners Fellowship (**REF5a-3.4**), and we support USS members to take up Flexible Retirement.

Research students

We attract world-leading PhD students to the Department, and have grown the PhD population in Warwick Computer Science from 51 in 2012-13 to 130 in 2019-20 (**Figure 5**, left). The growth has been encouraged by investment in studentships from Departmental and University funds (current annual levels approximately £900k and £300k, respectively). We also offer externally-funded opportunities, such as CDT positions (typically co-funded with industry), iCASE awards

and other scholarships (e.g. the philanthropically funded Feuer International Scholarships in AI). Industry-funded studentships have come from JLR (five), AWE (four), Intel (two), Rolls-Royce (two), AT&T, GE Omnyx, IBM, Microsoft, and Philips Healthcare, among others. Promising taught students can gain research experience through on-campus paid summer internships and the Data Science for Social Good summer programme. We hold briefing events to demystify the PhD process, with an emphasis on appealing to a diverse audience. Consequently, the quality of applicants is high. In 2020, 10% of the University's prestigious Chancellor's International Scholarships were awarded to students in Computer Science, even though this Unit contributes only 3.5% of Warwick staff submitted to this REF.
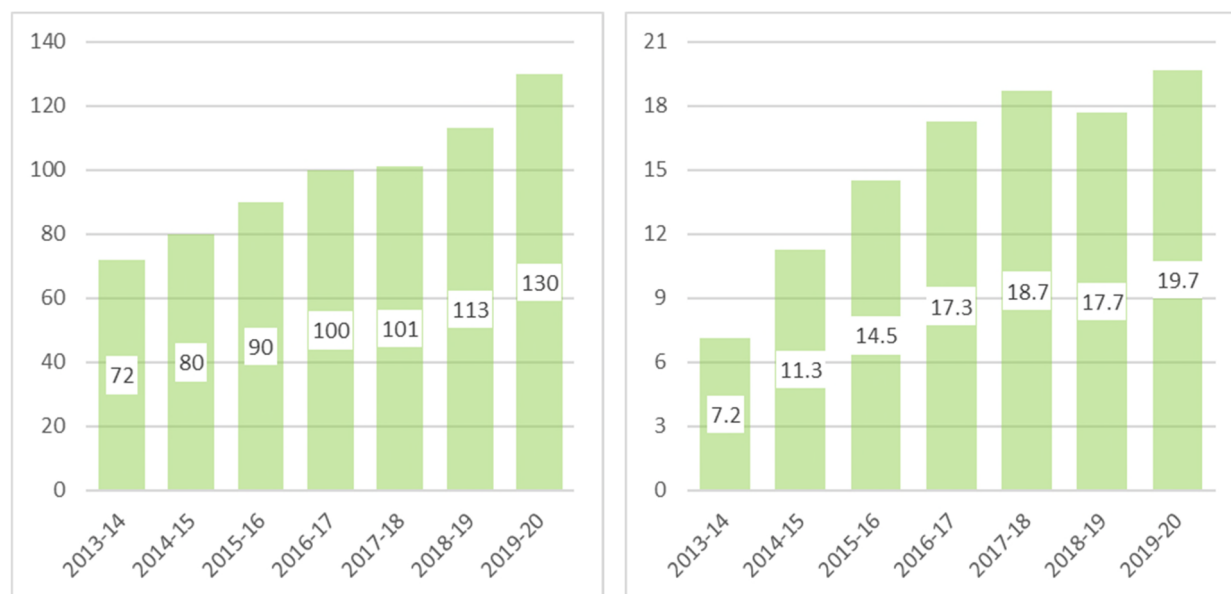

Figure 5. PhD populations (left) and conferrals (right) during the assessment period

During this REF period, the postgraduate research (PGR) community has been brought together organisationally and physically. Building on the success of the interdisciplinary Urban Science CDT hosted in Computer Science, all PhD students are inducted into a Departmental CDT structure. This ensures a uniform approach to excellent training and peer support for all members. It is led by a Deputy Head of Department *(Ferhatosmanoglu),* and supported by a full-time Postgraduate Research Manager. In addition to their supervisor, each PhD student has two advisors who offer independent guidance. PhD students are frequently co-supervised with different departments, most notably CIM, Engineering, Statistics and Warwick Manufacturing Group (**REF5a-1.6),** enabling a diversity of disciplinary views. In such cases, the fractional supervision contributions of our Unit are used when computing the PhD conferral numbers (*Figure 5*, right). Every student in the Urban Science CDT collaborates with an external partner, and many other PhD students have similar collaborations, leading to internships (e.g. Amazon, IBM, Palace of Westminster, Tableau and Yahoo) and placements at top research centres (e.g. Berkeley, INRIA, Loria). Eight PhD students have taken up enrichment years at the ATI. PhD students have won four University teaching awards in 2014-20, and in 2019 the Department received the first UK Facebook PhD Fellowship (supervisor *Damoulas*). Together with our postdocs, PhD students benefit from dedicated laboratory and social spaces built in 2018, annual away days, annual Faculty and Departmental research prizes, opportunities to teach (with appropriate training), our annual PhD conference, extensive training addressing scholarship and impact, personal development workshops on issues including imposter syndrome and self-sabotage, and full maternity leave offered by the Department. PhD students receive competitive stipends and a

personal budget of £2k per year for equipment and travel. Most Warwick PhDs progress to postdoctoral careers in research-focused organisations (e.g. ARM, AWE, GCHQ, Google, Intel, LANL, LLNL, MPI) and universities (e.g. Charles Prague, Harvard, ICR London, Imperial, IST Austria, Oxford, York, WPI).

Construction of the REF submission

Our REF submission was developed in line with the University's agreed Code of Practice (CoP – **REF5a-3.5**) by a five-person gender-balanced working group (three male, two female) consisting of the Head of Department, a senior professor, academic colleagues responsible for outputs and impact, and the Head of Administration. The Head of Administration's role was specifically to ensure adherence to the CoP at all times. All members of the group undertook REF-specific ED&I training to mitigate against unconscious bias (**REF5a-3.7**). The overarching criterion for selecting research outputs and impact case studies was excellence. Candidate publications were discussed in individual meetings of the working group with each eligible researcher, and assessed in collaboration with the heads and deputy heads of the research themes and the head of CIM, as well as through external reviews by 15 eminent UK academics. Before external review, all relevant colleagues were invited to comment on potential conflicts of interest, further mitigating against the possibility of bias.
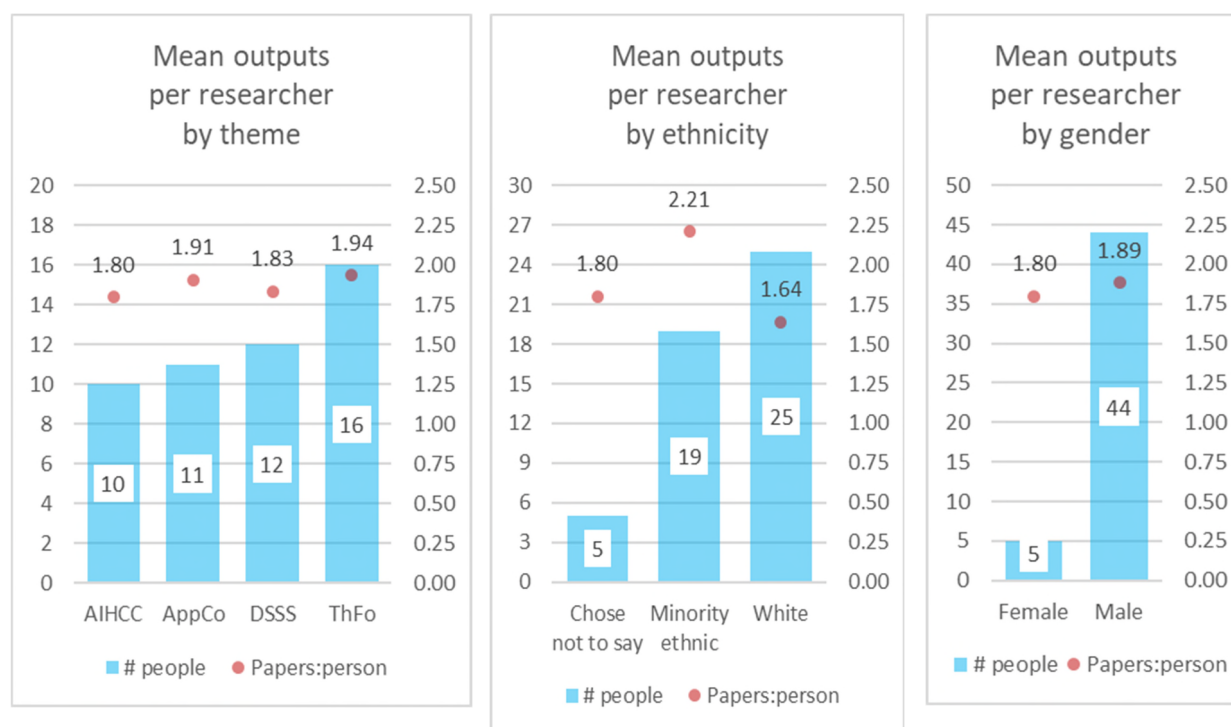

Figure 6. Mean numbers of submitted outputs per researcher by category

This approach has resulted in a good balance of outputs being selected across research themes and academics of different ethnicities and genders (*Figure 6*, which includes the leavers in this submission, who are two staff in the **ThFo** theme).

3. Income, infrastructure and facilities

<u>Research income strategy</u>

Delivering on our research and impact plans entails an ambitious growth strategy for income. We need resource in order to achieve the capacity required for larger projects, and to fund the specialist infrastructure needed to move into new areas (such as those involving HPC and AI) and maintain collaborations with industry. Funding for visits and exchanges, including for postdocs and PhD students, is key to our ability to play a full part in the international research community. The ability to employ a healthy population of postdocs and PhD students provides capacity and underpins the future sustainability of our discipline. The vibrant environment that we have built attracts excellent people, including those bringing prestigious independent fellowships to Warwick (e.g. *Gur*, *Hao*, *Král'*, *Oliveira*), which allows us to further invest in our research environment. Our resourcing strategy is based on maintaining a virtuous circle of investment, funding success, and re-investment.

New opportunities are flagged by Research Strategy Committee and R&IS (**REF5a-1.7**), who assist with bid development. Research themes play a key role in ensuring that the quality of bids is excellent, by peer-reviewing applications and mentoring junior colleagues in funding strategy. Within Computer Science, we run a research incentive scheme, whereby 50% of any surplus on an award is allocated as discretionary funding for the PI's theme, to be spent flexibly to support the development of new research initiatives. This represents an investment of approximately £450k per year in Departmental funds. Activities are further pump primed by engaging with University schemes such as those operated by the Institute of Advanced Study (IAS – **REF5a-2.9.2**) and Warwick Ventures (WV – **REF5a-2.8**). Computer Science recently hosted an IAS-WV Early Career Innovation Fellowship which has developed into a further funded impact-focused post. The Department has helped secure major awards and ensure their success by contributing studentships (e.g. ASiMoV – **page 20**), Assistant Professorships (e.g. PathLAKE – **page 20**), equipment and facilities such as data storage (e.g. *Y He*'s newly awarded Turing AI Acceleration Fellowship).

By implementing this strategy, we have succeeded in (1) securing **£15.8M** in research income during this REF period, compared with **£6.1M** during the previous one, (2) continuing throughout this REF period the monotonic pattern of growth in annual overall research income (*Figure 7*) that we also had during the previous one, and (3) increasing research income per submitted FTE to **£79k** in 2019-20 from **£71k** in 2012-13. A by-product of our strategy is resilience in the context of the evolving funding landscape. In particular, through growing our engagement with the ATI over the past four years we have benefitted from over £1M in research income within the "UK government bodies and charities" category, and we have developed new relationships with external funders of research, such as the Food Standards Agency.

<u>Organisational infrastructure supporting research and impact</u>

The theme discretionary funds provide flexibility to fund PhD students, bridge appointments of postdocs, organise events, support visitors and interns, and cover equipment and travel expenses. Supported by themes, our researchers (including PhD students) attended on average two international conferences or workshops organised at Warwick annually over this REF period, and collaborated with over 70 academic and industrial visitors from over 20 countries.
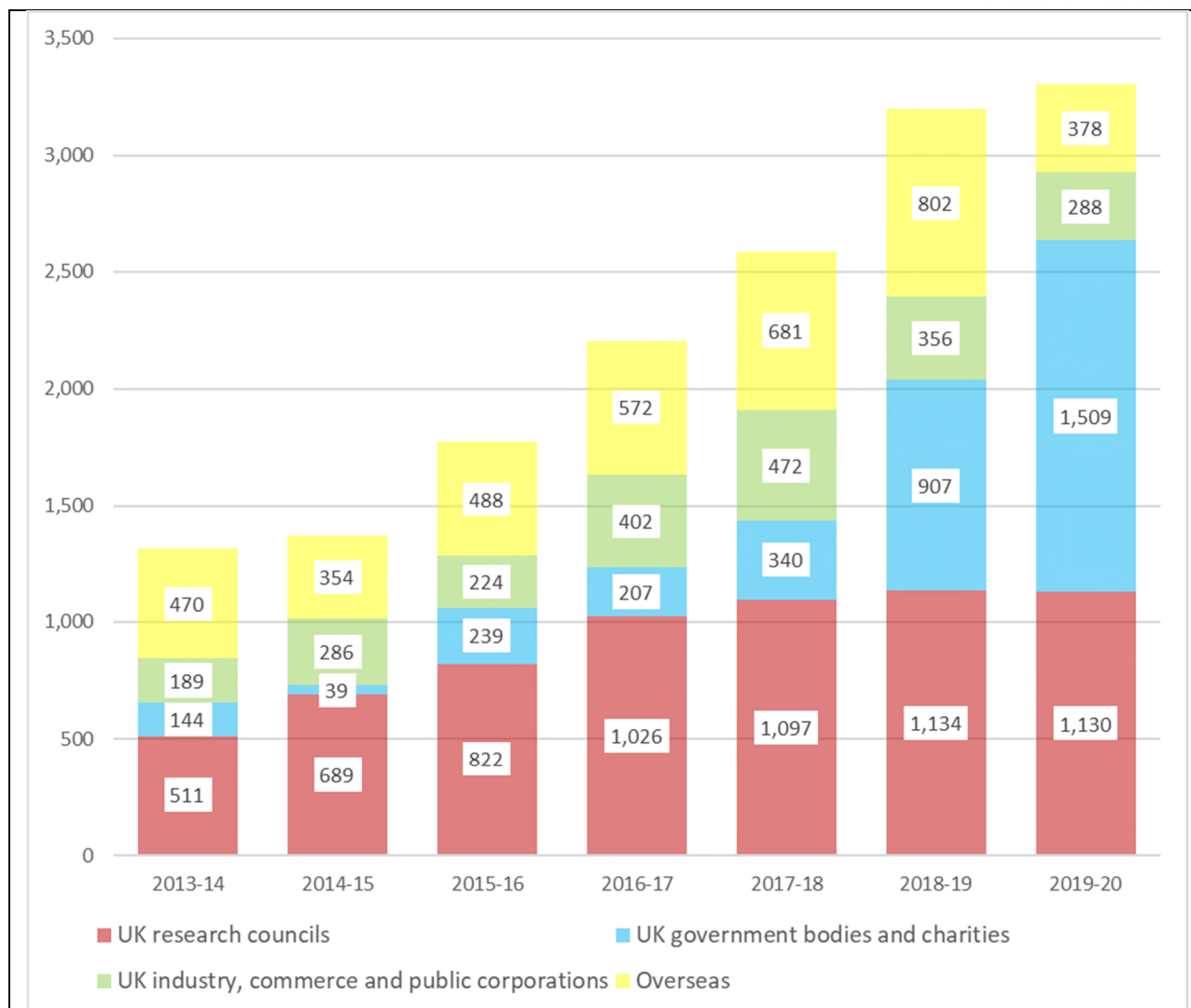
Figure 7. Research income totals by category of funder (£k)

At University level, we engage with WV to create commercial routes to impact for our research outcomes where appropriate. For example, building on research of *Hao*, we filed a patent on auctioneer-free e-auctions in 2019, and plan a spin-out to bring e-voting to market in 2021. Working with WV, we secured £15k of iCure funding to support a 3-month training programme to prepare one of our Research Fellows to become CTO of a forthcoming spin-out.

We are able to draw on institutional infrastructure such as R&IS (**REF5a-1.7**) to support the development and delivery of large and complex collaborative projects, including dealing with specialist IP, ethics and insurance issues, negotiating consortium agreements, and managing post-award administration. We also encourage and facilitate the development of such projects locally by providing suitable administrative leadership, for example, for the IDENTITY project (**page 20**).

The EPSRC CDT in Urban Science, the EPSRC CDT in Mathematics for Real-World Systems, and the Warwick CDT in Computer Science, through which most of our PhD students are supported, have all promoted and facilitated collaborations with business, industry, and the public and third sectors. Approximately one third of our population of 130 PhD students are fully or partially funded by such organisations.

Specialist research infrastructure and facilities

Our physical infrastructure is modern, bespoke and cohesive. Most researchers in our Unit are housed either in our purpose-built four-storey Computer Science Building, adjacent to the Warwick Mathematics Institute and the Department of Statistics, or in the new interconnected £27M, 3,700m^2 Mathematical Sciences Building. The new building opened in October 2018 and was part-funded by a £2M donation from the Wolfson Foundation. It represents a significant investment by the University, reflecting its vision of growth for its world-class mathematical sciences research.

The Computer Science Building has three air-conditioned server and communications rooms with a total area of 85m^2, containing a Slurm batch cluster with GPU nodes, over 20 high-power multi-GPU workstations, and over 250 high-specification Linux workstations with solid-state home storage. The Mathematical Sciences Building houses the Turing wing, where we accommodate visiting researchers from the ATI; SBIDER, to which we contribute a suite of rooms used by researchers and PhD students from Computer Science, Mathematics and Life Sciences; CDT study and social spaces; a large PGT laboratory and seminar room; and state-of-the-art video conferencing facilities.

In order to support our computational pathology impact pipeline (**page 20**), we led the specification and procurement of a £400k 2-petaflops DGX-2 deep learning AI supercomputer featuring 16 NVIDIA V100 Tensor Core GPUs, and a £280k IBM Elastic Storage System with initial capacity of 1.2 petabytes and with a dedicated IBM Spectrum Discover data lake management system. The Department also contributed financially to this equipment. This has enabled us to win a further £1.7M in NHS capital funding for PathLAKE Plus: upscaling our supercomputing and storage capabilities allowing us to build a unique global facility in computational pathology which will cover 46% of the population of England and Wales.

We contribute to the Scientific Computing RTP, both financially and through technical collaboration, in order to support our HPC impact pipeline. This facility hosts a hybrid system containing 14,336 x86 compute cores which reach a combined performance of approximately 0.5 petaflops, and an OpenPower component for large scale in-memory analytics. It represents a £3.2M capital investment by EPSRC, with a further new award of £3M for a Tier 2 HPC machine serving the Mid+ consortium and enabling massive ensemble computing.

ED&I is an important consideration in the design and evolution of our facilities. Our buildings provide gender-neutral, single-sex, and accessible toilets. Mobility issues or other adjustments are taken into account when allocating and fitting out offices, and we provide all equipment necessary for working from home. Since working with COVID-19 restrictions, our technicians have increased the number of CPU cores available for remote access from 80 to 280, and integrated them into a new load balancing system. This has been particularly important in ensuring equality of access for older colleagues and those in other high-risk groups.

Future plans

An important component of our research funding strategy is to encourage applications for longer larger grants which include significant buy-out for PIs and funding for postdocs, providing stability alongside capacity. Examples of recently awarded projects include two five-year Turing AI Acceleration Fellowships (*Damoulas*, *Y He*), with a total value of £2.4M, starting early in 2021. In our near-term pipeline are four UKRI FLF applications and two EPSRC fellowships.

A second component is to continue to bid for significant funding for collaboration with industry. This will further develop our relationships with existing industrial partners and initiate new relationships, ensuring that the potential impact of our work is fully realised. For example, we expect to extend our research programme with Huawei (*Triantafillou*), and we have recently won a grant from WM5G (*Ferhatosmanoglu*) with new commercial partners Blacc, Immense, one.network and O2.

We will continue to support the Warwick CDT in Computer Science, funded jointly with industry, in order to further nurture interdisciplinary collaborations and further develop PGR relationships with external partners, in preparation for the next UKRI CDT call.

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

Effective research collaborations are central to our pursuit of excellence. We collaborate in order to ensure that our research stays at the forefront of our discipline worldwide, that it remains fresh and relevant, and that it can achieve the scale and reach needed to make a real difference to the research base, economy and society. We lead in global academic networks, maintaining close links with colleagues at top universities in the UK and overseas, through joint research projects, shared supervision of PhD students and other collaborative activities such as the joint organisation of conferences. We maintain a number of strategic partnerships with the users and beneficiaries of our research and other stakeholders, which enrich our research environment by giving us access to real-world problems and data, and which offer routes to impact. We develop these partnerships partly through targeted engagement with external organisations, and partly through public engagement. Research-led outreach ensures the future sustainability of our discipline. We achieve this by inspiring young people and supporting computer science in schools, by recruiting the best taught and research students, and by maintaining close links with our alumni working in research-intensive organisations.

Arrangements and support for research collaborations

Our workload model ring-fences time for developing joint research proposals, and provides flexibility to engage in critical collaborative research activities even when these coincide with teaching or administrative duties. Our research incentive scheme (**page 16**) ensures that all colleagues have funding to attend conferences and workshops, and to visit national and international collaborators.

Exemplar: theoretical computer science – Collaboration is a defining characteristic of our research in theoretical computer science, which is led by the **ThFo** theme and takes place within the interdisciplinary DIMAP centre (*Table 1*). Established by a £3.8M EPSRC Science and Innovation Award (2007-2014), and bringing together researchers from Computer Science, Mathematics and Business, DIMAP has won over £10M of further funding, including prestigious awards from ERC (six), UKRI FLF (two), RS URF (two), and Leverhulme RF schemes. During this REF period, DIMAP has hosted over 20 conferences or workshops, featuring Nevanlinna Prize and Turing Award speakers such as Goldwasser, Kleinberg, Shamir and Valiant. **ThFo** also established the Highlights of Algorithms international conference series, held since 2016 in Paris, Berlin, Amsterdam, Copenhagen, and (virtually) Zürich, through the Interest Group on Algorithmic Foundations of Information Technology (IGAFIT) of which *Czumaj* is a founding member. The outputs contributed by the **ThFo** theme to this REF are results of collaborations with co-authors from 37 institutions in 15 countries, including Berkeley, CMU, École Polytechnique, Google

Research New York, IMSc Chennai, TU Munich, ENS Paris, MPI Saarbrücken, Technion, Vienna, Warsaw and ETH Zürich.

Exemplar: digital forensics – Our digital forensics programme, led by the **AppCo** theme, is a second exemplar of effective collaboration. During this REF period, our digital forensics researchers attracted £3.2M of funding from the EC, EPSRC, DSTL and the Royal Society, with an explicit focus on collaboration. In particular, the EU H2020 RISE project "IDENTITY" (*Li*, £1.4M) enabled knowledge transfer among research institutions and private companies about methodologies for identification in a forensic context. The research focused on imaging device identification for multimedia forensics, and on people identification for biometric forensics, across a network of 16 organisations from 14 countries in Europe, Asia, Australia, North America and South America. Our dedicated project manager ensured that over 80 secondments took place globally within a four-year period, involving early career and experienced researchers.

Development of impact and consequent enrichment of our research environment

Relationships with key users are nurtured, often starting with small-scale activities such as co-funding a PhD student, and developing into large collaborative programmes funding multiple students and postdocs and involving industrial, academic and third-sector partners.

Exemplar: intelligent vehicles – Developed from an iCASE studentship with JLR on detecting and modelling the current cognitive workload of a driver, enabling personalisation of the driver assistance and safety systems for the current driving conditions (2011-2015), the partnership with JLR led by *Griffiths* (**AIHCC** theme) has led to another iCASE studentship, a RS Industry Fellowship, and a £2M "The Cooperative Car" EPSRC-JLR TASCC five-year award. Involving three PhD students and six postdocs in Computer Science, Psychology and Business departments at Warwick, and working with Intelligent Systems and Human Factors groups at JLR Research, the project is enabling vehicles to cooperate with each other, with centralised control and data archival facilities, and with urban transport infrastructures. It has also developed methods for assessing the human perception and acceptance of autonomous vehicle features, such as highway self-driving, in different traffic and road conditions, which will enable manufacturers to appropriately tune autonomy systems.

Exemplar: HPC work with Rolls Royce – Building on £550k of PhD and postdoc funding from Rolls Royce, and two Royal Society Industry Fellowships with Rolls Royce, in 2018 *Jarvis* and *Mudalige* (**DSSS**) secured £1.8M through the EPSRC and Rolls Royce Prosperity Partnership "Computational Science for Advanced Simulation and Modelling of Virtual Systems (ASiMoV)". A collaboration with Bristol, Cambridge, Edinburgh and Oxford universities, it is the largest HPC focused research project in the UK in recent times, worth £14.7M in total over five years, and aims to achieve the world's first high-fidelity simulation of a complete gas-turbine engine during operation, simultaneously including the effects of thermo-mechanics, electromagnetics and computational fluid dynamics.

Interdisciplinary research, and responding to national and global challenges

We address national and global challenges by undertaking interdisciplinary work with clear paths to impact, engaging with the University's GRP networks (**REF5a-2.9.1**).

Exemplar: computational pathology – *Rajpoot*'s research programme (**AppCo**), which has grown into the Tissue Image Analytics (TIA) centre linked to the Health GRP, is associated with

University Hospitals Coventry and Warwickshire NHS Trust's global leadership in digital and computational pathology. The work was seeded by a PhD studentship with GE Omnyx on "IHC Stained Slides of Serial Sections" (2013-2016) and a Warwick EPSRC IAA award "Computerised Profiling for Improved Diagnosis and Stratification of Oral Cancers in the Indian Subcontinent" (2016-2017). *Rajpoot*'s involvement in the Warwick team was instrumental in Omnyx's decision to locate their UK technology demonstrator site at UHCW. Subsequent PhD studentships from Philips PathXL with MathSys (*Table 1*) and from Intel with ATI (**page 5**) increased the capacity of *Rajpoot*'s group, gave access to further real-world problems and associated data, and extended relationships with industrial and NHS partners, leading to a range of opportunities for impact. The resulting outputs and developing impact led to the award of £570k of MRC grants, and £2.3M from Innovate UK to lead the computational arm of the "Pathology image data Lake for Analytics, Knowledge and Education (PathLAKE)" project (2018-2021), a national Centre of Excellence on AI in pathology. The £15M project, conducted by a consortium involving our local UHCW trust as the project lead as well as teaching hospitals and universities at Belfast, Oxford and Nottingham, and also Philips, Nvidia and four SMEs, is meeting the UKRI ISCF challenge "Data to early diagnosis and precision medicine". Most recently, the work of the TIA centre on highly accurate classification of cancers has been complemented by a new collaboration with GSK, currently funding three PhD students, seeking to extend the application domain to personalised medicine.

Exemplar: management of flooding in Brazil – *Porto de Albuquerque* (**AIHCC** and IGSD – **Table 1**) has developed a programme of research across three different grants: "UK-Brazil Collaboration on Leveraging Crowdsourced and Sensor Data to Support Decision-Making towards Urban Resilience" (PI, EPSRC GCRF, £50k, 2016-2017), "Global Health Unit on Improving Health in Slums" (Co-I, NIHR, £6M, 2017-2021), and "Waterproofing Data: Engaging Stakeholders in Sustainable Flood Risk Governance for Urban Resilience" (PI, ESRC GCRF, €1m, 2018-2021). This has led to the development of: (1) a participatory design methodology to enable low-income communities to co-design data collection tools and generate high-quality geospatial data, (2) a novel conceptual modelling framework to support data-driven decision-making, and (3) an innovative geocomputational data integration method which enables the incorporation of citizen-generated data to support flood monitoring. These developments have been used by Brazil's National Centre for Monitoring and Alerts for Natural Disasters (CEMADEN) to improve the speed, accuracy and operational effectiveness of the information it supplies to organisations throughout the country. It also enabled flood-prone, low-income communities in Brazil to generate flood-related data and gain access to early-warning systems. This research is being continued via a Global Research Translation Award (co-PI, UKRI GCRF, £370k, 2019-2021) and project "URBE Latam: Understanding Risks and Building Enhanced Capabilities in cities of Latin America" (PI, UKRI GCRF, £900k, 2019-2022), expanding the geographical scope within Brazil and to Colombia.

Wider contributions to economy and society

Further exemplars have been facilitated by our support for impact through engagement with the ATI, as well as through schemes such as Knowledge Transfer Partnerships and IAS-WV (**REF5a-2.8** and **REF5a-2.9.2**) Early Career Innovation Fellowships.

Exemplar: contributions through cyber security and human-centred computing – Based on research funded by ERC and Innovate UK, *Hao* (**DSSS**) led the first successful trial of an end-to-end verifiable e-voting system for polling station voting in Gateshead during the May 2019 local elections, and is the PI of a follow-on Royal Society project (£210k, 2018-2021) whose goal is to bring this technology to bear on voting systems in India. Another contribution to public life is from

Procter's work (**AIHCC**) in collaboration with Cardiff, De Montfort and Oxford, and sponsored by ESRC and Google, which has fed into the UK Government's Online Harms White Paper. *Procter*'s research with Oxford, funded by NIHR and TSB, has contributed to the development of the Non-adoption, Abandonment, Scale-up, Spread, and Sustainability (NASSS) framework, which is being delivered as a toolkit through the mHabitat co-design, digital innovation and inclusion team hosted by Leeds and York Partnership NHS Foundation Trust, and has been used in teaching by the NHS Digital Academy. A further contribution in the health domain is an ongoing study of *Liakata* (**AIHCC**) in collaboration with the Warwick spin-out Clinvivo on NLP techniques for predicting the progression of dementia by analysing patients' speech or writing, which has been adopted by the West Midlands Clinical Research Network.

Exemplar: societal impact with the ATI – Much of the Unit's work in collaboration with the ATI is directly socially beneficial. We pioneered bringing the Data Science for Social Good summer programme to the UK in collaboration with the ATI, face-to-face in 2019 and online in 2020, bringing together participants from around the world over three months to learn data science skills and apply them to real world problems. This delivered actionable insights and tools for six socially-minded organisations (Homeless Link, Ofsted, WMCA, Cochrane, Paraguay National Directorate of Public Contracting, and the World Bank). The program spans departments, including Computer Science (led by *Cormode*, **DSSS** and ATI University Lead), Mathematics, Statistics, Business and CIM. A second ATI example is Project Odysseus (PI *Damoulas*, **DSSS**), which builds on spatiotemporal statistics. The original focus was air quality monitoring in cities, funded by GLA, but in March 2020, the team pivoted to address their efforts to the monitoring of human activity during lockdown. Project outputs are now part of a package available to high street managers that also includes anonymised and aggregated people counts from mobile phone providers and spend data. In the short to medium term, the impact is that borough staff across London are able to make better-informed decisions about how they reopen the high streets safely. In the longer term, it feeds into the more strategic work to support high streets to adapt and recover post COVID-19. A third example is the "Advanced Analytics in the UK Food & Drink Sector" project (2019-2020, PI *Procter*, **AIHCC**), which has provided the Food Standards Agency with a state-of-the-art summary of the latest developments and issues in the application of advanced data analytics to food safety and authenticity for improved system trust.

Research-led outreach and engagement

Our schools outreach programme aims to increase the participation of underrepresented groups in computer science. We develop sustained relationships with local schools, for example PlayCodeShare enables primary and secondary schools to explore a new creative model of teaching programming. Our researchers contribute to summer schools, such as Headstart (2014-2016) and Sutton Trust (2018-2020). We have been providing Continuing Professional Development (CPD) to teachers on behalf of the National Centre for Computing Education throughout this REF period. *Leeke* (**DSSS**) serves as a scrutineer and exam writer for AQA Education.

We contribute to public outreach events (e.g. Festival of the Imagination 2015, Cheltenham Science Festival 2015, British Science Festival 2019, IF Oxford 2020, A Slice of Science 2020), and to Faculty and University research showcases (e.g. Industry Days, to which local and regional companies are invited). We also support our research projects in their public engagement activities, such as the PathLAKE (**page 20**) Masterclasses, CPD accredited by the Royal College of Pathologists, and aimed at computer scientists, engineers, data scientists, and pathologists, to gain familiarity with data science techniques for solving computational pathology problems.

Indicators of influence, contribution and recognition

Editorial Board memberships – In total 29, including: Editor-in-Chief of SIAM Journal on Discrete Mathematics and Managing Editor of Advances in Combinatorics (*Král'*); Associate Editors of ACM Transactions on Database Systems (*Cormode*), IEEE Security & Privacy (*Hao*), IEEE Transactions on Learning Technologies (*Joy*), Information Processing Letters (*Lazić*); Editors of Performance Evaluation (*Ciucu*), Psychological Medicine (*Feng*), Service Oriented Computing and Applications (*Griffiths*), Health Informatics (*Procter*), Medical Image Analysis (*Rajpoot*), Computers and Graphics (*Turkay*), Multimedia Tools and Applications (*Yu*).

Fellowships[6], prizes and awards – Selected list: ACM Fellow (*Cormode*), EATCS Fellow and President (*Czumaj*), AWE William Penney Fellow and TRL Academy Fellow (*Jarvis*), AMS Fellow (*Král'*); Adams Prize (*Cormode*), Shimon Even Prize (*Gur*), Philip Leverhulme Prize (*Král'*), Roger Cotton Prize (*Rajpoot*); Imre Simon Award (*Cormode*), Wolfson Research Merit Awards (*Cormode*, *Feng*, *Rajpoot*, *Sviridenko*), IBM Faculty Award (*Czumaj*, *Liakata*), Georg Forster Research Award (*Ferhatosmanoglu*), ITC Rising Scholar Award (*Mukhopadhyay*), EuroVis Young Researcher Award (*Turkay*).

National and international committee memberships – Selected list: Chair of the Maestro Advanced Grant panel at the Polish NCN, Chair of the LMS Computer Science Committee, UK Computing Research Committee (CRC) (*Czumaj*); Advisory Committee for the National Science and Technology Research Council of Turkey (*Ferhatosmanoglu*); Executive Committee of the Association for the Advancement of Affective Computing (*Guha*); SafeToC (*Gur*); Computer Science panel of the Czech Science Foundation and Dénes König Prize Selection Committee (*Král'*); Natural England Science Advisory Committee (*McInerny*); UKRI GCRF Strategic Advisory Group (*Porto de Albuquerque*); Board of Directors of the International Foundation for Autonomous Agents and Multiagent Systems (*Tran-Thanh*); ADAPT Centre review panel of Science Foundation Ireland (*Procter*); REF 2021 Sub-panel 11 and UK CRC (*Triantafillou*).

Conference leadership roles – These include: Steering Committee members of Annual European Symposium on Algorithms, Highlights of Algorithms, and International Colloquium on Automata, Languages and Programming (ICALP) (*Czumaj*), ACM-SIAM Symposium on Discrete Algorithms (SODA) (*Král'*), Medical Image Understanding and Analysis (*Rajpoot*), ACM/USENIX/IFIP International Middleware Conference (*Triantafillou*); Advisory Board members of Proceedings of Very Large Databases (*Cormode* and *Triantafillou*); President of the European Congress on Digital Pathology 2019 (*Rajpoot*); Programme Committee Chairs of SODA 2018 and ICALP 2020 Track A (*Czumaj*), Highlights of Logic, Games and Automata 2018 (*Jurdziński*), Canadian Discrete and Algorithmic Mathematics Conference 2019 (*Král'*); Programme Committee Co-Chairs of International Conference on Cryptology in India 2019 (*Hao*), Conference on Empirical Methods in Natural Language Processing 2020 (*Y He*), International Symposium on Mathematical Foundations of Computer Science 2020 (*Král'*); Open Practices Chair for IEEE VIS 2019, 2020 (*Turkay*).

Invited keynotes – Over 120 conference and workshop invited talks, including: Highlights of Logic, Games and Automata 2019 (*Chistikov*); International Conference on Analytical and Stochastic Modelling Techniques and Applications 2016 (*Ciucu*); ACM SIGMOD-SIGACT-SIGAI Symposium

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[6] Fellowships that are research grants are covered elsewhere in this template, see e.g. **Work Strand I** on **page 4**.

on Principles of Database Systems 2015 and ACM Symposium on Principles of Distributed Computing 2018 (*Cormode*); IEEE International Conference on e-Business Engineering 2013 (*Griffiths*); SIAM Conference on Discrete Mathematics 2018 and International Conference on Random Structures and Algorithms 2017 (*Král'*); IARCS Annual Conference on Foundations of Software Technology and Theoretical Computer Science 2019 (*Lazić*); International Statistical Ecology Conference 2014 (*McInerny*); SPIE Digital Pathology 2020 (*Rajpoot*); Eurasia Graphics 2014 (*Turkay*).

Invited tutorials for doctoral students – These include: 14th Summer School on Modelling and Verification of Parallel Processes (online), Grenoble, France, 2020 (*Chistikov*); German-Israeli Workshop and Winter School on Algorithms for Big Data, Tel Aviv, Israel, 2017 (*Czumaj*); Efficient algorithms in game theory, optimization and data science, Aachen, Germany, 2015 (*Englert*); IX Escuela de Verano en Matemáticas Discretas, Valparaíso, Chile, 2014, 9th PhD Summer School in Discrete Mathematics, Rogla, Slovenia, 2019, AlgoMaNet School, Brno, Czechia, 2020 (*Král'*); EPSRC Sustainable Approaches to Biomedical Science: Responsible and Reproducible Research, Oxford, UK, 2019, Visualization Summer School, Beijing, China, 2019 (*Turkay*).