

Institution: Cardiff University
Unit of Assessment 11: Computer Science and Informatics
1. Unit context and structure, research and impact strategy 1.1 Overview The School of Computer Science and Informatics (COMSC) at Cardiff University has seen a transformation of our research environment and size since REF2014, enabled by sustained and significant investment in infrastructure, culture and support for our staff. Our vision is to undertake fundamental research that allows us to address real-world challenges. Our approach to fundamental research is based on an ethos of interdisciplinary partnerships and co-creation that generate impact by addressing societal and business challenges. This involves an inclusive School-wide culture of curiosity, collaboration, and creativity to support ambition and innovation, empowering staff at all stages of their careers to pursue their individual research agenda. Since REF2014, highlights of progress in research, impact and people include: • Strengthening research critical mass by nearly doubling our category A staff to over 45 FTE; • Tangible benefits from our commitment to equality, diversity and inclusion, including category A staff representing 13 countries and 23% female (rising from 15% in 2014), with the proportion of female PGR students rising from 36% to 39% (vs 28% across sector); • Renewal of the Athena SWAN bronze award; • Achieving 25 (22%) of our REF submitted research outputs in the top 5% field-weighted citation profile (SciVal); • Generating impact through cross-disciplinary collaboration with leadership and partnership in five large-scale University Research Institutes/Centres while building on strategic relations with Airbus, IBM and Tencent; • Securing long-term sustainability through the launch of the <i>Data Science Academy</i> and the <i>Wales National Software Academy</i>, which provide new routes to engage business for collaboration and impact; • Providing an exemplary collaborative research environment by securing University funding for a purpose-designed building due for completion in September 2021. 1.2 Research and Impact Strategy Our strategy for this period, as outlined in our REF2014 submission, comprised three principal objectives: • Implement further plans for larger research initiatives; • Prioritise cross-discipline collaboration; • Develop challenging research agendas through relationships with strategic partners. Strong progress has been made against each of these objectives. Firstly, we targeted substantial growth through new staff appointments and support for early career researchers (ECRs) facilitating delivery of larger research initiatives. Following REF2014, Cardiff University recognised that COMSC needed greater critical mass to achieve our research potential and deliver impact across disciplines, leading to a sustained programme of investment in staff and facilities. Consequently, our staff FTE has increased to 45.55 FTE with 20 staff appointed to their first lectureships (Section 2.2). The benefits have already been apparent over the REF period, with mean annual research income growing by 24% to £2.1m, PhD student numbers increasing by 49% (to 61), with ECRs achieving successes including an ERC Starting Grant, and major initiatives of £29.9m led/co-led by School members (Section 1.5). In 2019, the University Council approved a £39m capital investment for Abacws, a new building that will collocate COMSC with the School

of Mathematics, accommodating our growth and providing a bespoke, high-quality research environment designed to support increasing cross-subject interactions (Section 1.3).

We have prioritised **cross-discipline collaboration** through leadership and engagement within five key interdisciplinary research centres covering Data Science, Cyber Security, Artificial Intelligence, Crime and Security, and the Social Sciences (Section 1.4). Finally, we have sought to strengthen our **primary strategic relations** (including Airbus, IBM, the Office for National Statistics (ONS) and Tsinghua University), which have shaped aspects of our research agenda (Section 4.1), leading to over £2m of funding, and generated international impact reaching the US and China (Section 4.1). This activity has strengthened our reputation and influence (Section 4.4); for example, Burnap has been appointed to the UK government AI Council; Schockaert joined the board of the European Association for AI; Preece has provided academic leadership for a major collaborative programme between Dstl and US Army Research Labs.

Achievement of our strategic aims is reflected in our impact case studies and impact highlights (Section 4.3). All four submitted cases are international in their reach (Airbus, Tencent, IBM, Simba Chain); three involve large research initiatives established during the period (Section 1.5). Our support for impact creation has increased over the period (Section 3.3) and we have dramatically increased the volume and breadth of our engagement with industry, interacting with over 250 companies at all scales. This has been achieved through the expansion of our External Advisory Board and a holistic approach to industry engagement covering research, skills and innovation, enabled by the launch of innovative teaching initiatives designed to address the digital skills gap in South Wales, targeting software engineering, data science, AI and Cybersecurity. Since its establishment in 2018, the WEFO-funded Data Innovation Accelerator (Section 4.2) has provided a further opportunity to connect SMEs with academic expertise, with involvement from 41 companies and 19 COMSC staff.

1.3 Future priorities

Our plans for the next period build on the successful elements of our REF2014 strategy through the following actions:

Sustainable growth. We will continue to grow sustainably while prioritising research and impact quality, funded by expansion of specialist master's programmes and supplemented with increased research income. We will ensure growth in staff and support matches any increase in the student cohort, with a commitment to increase workload capacity for blue-sky exploratory research, impact and funding applications. Our aim is to grow critical mass to introduce a further two coherent and distinctive high-level research sections within the next 3 years (Section 1.4), with a bottom-up approach to invest in areas aligned to ensuring an inclusive, vibrant research culture and high levels of external engagement.

Exploit opportunities of Abacws building to make a step change in our research culture and capability. We will increase collaboration with Mathematics, particularly in AI and Data Science, to develop our new strategic partnership with the ONS (Section 4.2), taking advantage of proximity to the new Innovation Campus (REF5a). The bespoke facilities will further enhance research engagement with industry, government and public, while also strengthening the involvement of our taught students directly in research, supporting a pipeline of future PGRs.

Support ECR career development. We will continue to primarily appoint at ECR/lecturer level, with targeted senior appointments where established leadership and experience is required. Equality, diversity and inclusion (ED&I) will remain at the heart of culture. The careers of our ECRs from REF2014 have progressed rapidly during this period (Section 2.3), and we will continue to improve the quality of strategic career development support for ECRs (both financial and mentoring), in line with the Concordat to Support the Career Development of Researchers. Particular support will be given to helping staff develop international networks and reputation.

Increase critical mass of PDRAs and PGRs while widening the recruitment pool. We aim to significantly increase externally funded research staff, targeting an average of at least one FTE per category A staff member. The introduction of a short-term research leave scheme

will release teaching workload to allow uninterrupted time to prepare large proposals, and we aim to give all staff this opportunity on at least one occasion during the next REF period. We will provide additional support for staff working with industry, KTP applications, bid preparation and internal review. Expansion of taught programmes will be exploited to increase our PGR cohort, with the aim of reinvesting 5% of our annual fee income on School-funded scholarships and improving PGR recruitment from our specialist master's students. Increased School-funded studentships will target more support towards ECRs and areas of future growth. We will increase the opportunity for undergraduate and master's students to gain practical experience through paid research internships as part of "year in industry" programmes and increase the range of flexible opportunities for PGR study to encourage more diverse applicants, including part-time positions, offered in combination with 0.5 FTE teaching associate posts.

Increase societal and business impact. Our approach to impact is based on developing long standing, meaningful relationships with other disciplines, other universities and industry. Building on our strong relationship with Tsinghua University, we intend to grow further international collaboration networks based on staff interests, further developing recent links with the Universities of Illinois and Waikato, and working with Welsh Government to engage industry in the US through emergent partnerships. We will refine our approach to industry engagement, with a particular target of local SMEs which form a large proportion of the Welsh industrial base. For example, we will develop initial connections arising through undergraduate industrial projects into collaborative research/impact funding applications. We will continue to support industrial experience for staff and research students through secondments and placements, an approach that supported our submitted impact case with Airbus.

1.4 Research structure

Our research activity is overseen by the School Board, and organised into three *sections*, each responsible for their respective strategy, as detailed below. All staff have a primary section membership with cross-disciplinary interactions and applications facilitated through secondary affiliation to Labs, Centres and University Research Institutes (see Institutional statement). A "bottom-up" approach to collaboration is enabled by encouraging smaller research groups within and across sections, proposed to the School Board by staff in focussed areas of interest. Twelve such research groups are currently active, including growth areas of Natural Language Processing, Data Analytics & Machine Learning, and Privacy. In addition to a School seminar series, all three sections run a programme of weekly meetings/seminars with internal and external speakers.

Since REF2014, the School has evolved and strengthened the three research sections through the recruitment of many new members (*italicised below*):

Research Section 1: Artificial Intelligence & Data Analytics (AI&DA)

AI&DA has an emphasis on Knowledge Representation and Reasoning (computational argumentation, description logics), Natural Language Processing (multilingual NLP, lexical semantics), Data Analytics & Machine Learning (statistical relational learning, representation learning) and Data Science (text mining, social media analysis, geographical information science).

17.1 category A staff FTE (4 female/13.1 male): Abdelmoty, *Booth*, *Camacho-Collados*, *Caminada*, *Corcoran*, *Espinosa-Anke*, *Gutiérrez-Basulto*, *Ibáñez-García*, Jones, *Kido*, *Liberatore*, *Polberg*, *Preece*, **Schockaert (leader)**, Shao, Spasić, *Treder*, Whitaker. Since REF2014: research staff: **21.6**; PGRs: **37** FTE (19 female/18 male); PhD completions: **23.3** FTE; publications in REF period: **481**; Grant awards: **£8.2m**

Highlights since REF2014: AI&DA staff have paid particular attention to raising their international profile through participation in major conferences (including IJCAI, AAAI, KR, ACL) and locally organised workshops, with a significant benefit to our recruitment of new staff and formation of new collaborations. Notable **outputs** in fundamental research include techniques to learn semantic relations from conceptual spaces to support plausible reasoning (Schockaert, *Artificial Intelligence Journal*); a new framework for reasoning about typicality in propositional logic (Booth, *Artificial Intelligence*); and inter-disciplinary modelling on the fundamentals of cooperation and

reciprocity (Whitaker, *Scientific Reports*). This is complemented by **applications and impact** in crime & security and healthcare, including advances and benchmark datasets for embeddings in NLP (Camacho-Collados, *NAACL*); association of violence with urban points of interest (Corcoran, *PLoS One*), and genetic programming for clinical prediction of symptomatic cardiovascular disease (Spasić, Preece, *PLoS one*). External research **funding** has supported long-term research agendas concerning situational understanding among human-AI teams (Distributed Analytics and Information Science International Technology Alliance (DAIS ITA), UK Ministry of Defence and the US Army Research Laboratory, Section 2.3) and formal lexically informed logics (Schockaert, European Research Council Starting Grant, £1.2m). Extensive collaborations with **industry** labs (Samsung AI, Tencent AI, Microsoft Research) have taken place, with particularly strong links to IBM Research, who have subcontracted over £1.9m of research to COMSC since REF2014.

The AI&DA Section's **future objectives** are to:

Further combine learning and reasoning, on which AI systems are increasingly reliant. AI&DA is uniquely positioned in this emerging field, given its strength in both symbolic reasoning and data-driven learning, and its expertise in making bridges between these two AI traditions.

Establish ourselves as a focal point for interdisciplinary NLP research. The AI&DA Section aims to expand critical mass of staff and PGR students in NLP research which combines lexical semantics, common sense reasoning, social media, multilinguality, and their applications, building on the research interests of recent appointments (Espinosa-Anke, Liberatore, Camacho-Collados) and the recent award of a UKRI Future Leader Fellowship (Camacho-Collados).

Research Section 2: Cybersecurity, Privacy & Human-Centred Computing (CP&HCC)

CP&HCC covers cyber systems that necessitate understanding of interaction between human and technology, including cybersecurity, collaborative & social computing, data privacy, human-computer interaction (HCI), ubiquitous & mobile computing, internet of things (IoT), while addressing issues of usability, accessibility, privacy, scale and complexity in our everyday digital experiences.

17.65 category A staff FTE (4.4 female/13.25 male): Allen, Burnap, **Eslambolchilar (leader)**, Finnegan, Fuentes, Javed, T. Li, Y. Li, Mumford, Perera, Rana, Reinecke, Saxena, Stawarz, Taylor, Theodorakopoulos, Turner, Verdezoto, Walker. Since REF2014: Research staff: **22.8**; PGRs: 51.5 FTE (24 female/27.5 male); PhD completions: **23.7** FTE; publications in REF period: **502**; Grant awards: **£5.0m**.

Highlights since REF2014: Notable **outputs** include the first predictive model to detect ransomware in real time (Burnap, *Computers and Security*), a novel approach of game theory to maintain location privacy (Theodorakopoulos, *ACM Transactions on Privacy and Security*); successful fuzzy text classification approaches to detect hate speech, in collaboration with Social Sciences (Burnap, *IEEE TCSS*); secure protocols for service delivery to mobile devices (Saxena, *IEEE TIFS*). Our **applied research** is typified by a mixed-methods approach to incentivising physical activity among children (Eslambolchilar, *JMIR Medical Informatics*); new approaches to malware detection (Burnap, *Computers and Security*); and a collaboration with Psychology on the nature of smartphone addiction (Turner, Whitaker, Allen, *Computers in Human Behavior*). External **funding** has supported our long-term research agenda and industry partnership with Airbus in data analytics for cyber security, increased staff capacity in HCI (IROHMS funding, Section 1.5) and infrastructure (HEFCW cyber range, Section 3.2).

The Section's **future objectives** focus on building critical mass in Cybersecurity and Human-centred computing, to allow both to become independent research sections:

Cybersecurity expansion reflects our success in cyber analytics based on a data science/AI approach, sustained growth (5 FTE new category A staff), exploiting the recent acquisition of our dedicated cybersecurity range (£1.2m HEFCW), and building on strong industry connections (CCSR, Section 4.2). Links to the wider GW4 environment will be reinforced, including a forthcoming Strength in Places submission (with Bristol, Bath, and Gloucester

Universities) linked to the Cardiff City Region Deal to create a sustainable Cyber Innovation Hub covering AI for cybersecurity research, and skills engagement.

Human-centred computing has been prioritised reflecting sustained growth (4 FTE category A staff) in the area since the appointment of Eslambolchilar, with a focus on a cross disciplinary approach to designing interactive systems to support self-reflection, self-monitoring, feedback, persuasion, immersion, and navigation, such as integration of face-to-face and digital approaches for mental health (Stawarz, *ACM CHI*).

Research Section 3: Visual Computing (VC)

VC encompasses research across computer vision, geometric computing, and computer graphics. This considers the analysis, understanding, generation and editing of images and 3D shapes, as well as time-varying data such as video and 3D video scans of moving objects, in particular faces. As well as devising a range of general-purpose algorithms in areas such as image and shape retrieval, image quality assessment, shape design for manufacturing, dedicated techniques as highlighted below are also developed to address real-world problems.

10.8 category A staff FTE (2 female/8.8 male): *Deng*, *Lai*, *Langbein*, *Liu*, **Marshall (leader)**, *Qin*, *Rosin*, *Sidorov*, *Sun*, *Wu*, *Zoumpoulaki*. Since REF2014: Research staff: **9.8 FTE**; PGRs: **29.5 FTE** (6 female/23.5 male); PhD completions: **15.5 FTE**; publications in REF period: **345**; Grant awards: **£1.7m**.

Highlights since REF2014: Notable **outputs** include a novel parallel solver for computing geodesic (*Deng*, *IEEE TPAMI*), objective image quality assessment models exploiting visual saliency and machine learning (*Liu*, *IEEE TNNLS*; *Lai*, *IEEE TPAMI*). The novel techniques developed by the VC Section have been applied in collaboration with **industry and other disciplines**, including the generation of panoramas for street view (*Lai*, *ACM Transactions on Graphics*, basis for an impact case study with Tencent) and virtual unrolling of fragile historical parchments (*Rosin* with Norfolk Record Office, *Scientific Reports*). External **funding** has enabled blue-sky applications, such as the use of 3D virtual avatars for remote medical consultations (Knowledge Transfer Partnership, Orbital Media) and a pilot deployment of facial recognition software during the Champions League final in Cardiff (with Police & Crime Commissioner for South Wales).

Future objectives focus on:

Targeting multidisciplinary funding to build sustainable groups in medical applications and computational architecture, reflecting interests of recent ECR appointments and building on links to the NHS and Cardiff University Brain Imaging Centre (CUBRIC). Instrumental to this strategy is the recent launch of the pan-Wales Industry Exchange Network, IXN Cymru, in collaboration with UCL who pioneered the model in England. IXN Cymru will facilitate proof of concept student projects in collaboration with a network of external stakeholders that have the potential to expand into future research funding.

Further develop impact with industry, exploiting our research success through strong links with companies such as British Aerospace, General Dynamics, Airbus, Renishaw and Tencent, through CASE studentships, KTP or other joint projects. As an example, our pan-School (ENGIN, CUBRIC) collaboration with Renishaw has been successful in investigating how to improve operational procedures that account for displacement of the brain due to gravity in different orientations, which we will move from prototype to clinical setting.

1.5 Interdisciplinary research

Wider **cross-discipline collaboration** and influence of our research is facilitated by leadership and membership of COMSC staff in labs, centres and University Research Institutes that have been established post REF2014. All staff are encouraged to join these in addition to their primary research section, enabling them to address **larger, interdisciplinary research initiatives**:

The **Crime and Security University Research Institute** (established 2015, co-director Preece, 12 FTE COMSC members) develops new insights, evidence and knowledge about national and international crime and security problems through collaboration with social sciences and life sciences at Cardiff University. Leveraging long-term, **strategic relationships** with Airbus,

Dstl, IBM and UK police forces, the institute directly influences how governments and security agencies respond to disruptive technologies, including the use of automated facial recognition and the influence of foreign state disinformation. In the current REF period, the Institute has led research programmes worth £20m from diverse sources including the UK, US and Canadian Governments, EPSRC, ESRC and MRC. Members of all three School research sections contribute to the Institute's research and development programmes, and experience gained from applying our research to challenging real-world problems (e.g. human-AI collaboration for situational understanding) helps identify gaps where further basic research is needed (e.g. explainable AI).

The **Data Innovation University Research Institute (DIRI)** (established 2015, co-director Spasić, 14 FTE COMSC members) is a focal point for fundamental research into data science and supports the application of these techniques to other disciplines across the University. The institute has joint leadership with the School of Mathematics and exemplifies the synergy between the two schools in combining theoretical and computational aspects of data science. The institute draws on expertise from all three colleges of the University, applying big data approaches to problems in the medical, biosciences, social sciences, physical sciences and engineering sectors. In addition to a dedicated Senior Lecturer appointment in the School (Y. Li), the institute supports the development of **cross-discipline collaboration** through a cohort (3 FTE) of Research Software Engineers available for seed corn projects (e.g., Modelling burns first-aid conversations on social media to shape a vital intervention, Wellcome Trust Institutional Strategic Support Fund). The institute is a focal point for the University's strategic partnership with the ONS (Section 4.2).

Cardiff University's **Centre for Cyber Security Research (CCSR)** (director Burnap, 9 FTE COMSC category A staff) unites 50 researchers from COMSC, Psychology, Social Sciences, and Law. CCSR focuses on the fusion of data science and artificial intelligence methods with interdisciplinary insights into cyber risk, threat intelligence, attack detection and situational awareness, from algorithmic and human factors perspectives. CCSR has attracted more than £6.3m of funding from EPSRC, ESRC, HEFCW, Industry and Government since 2014. CCSR was recognised as an **NCSC/EPSC Academic Centre of Excellence in Cyber Security Research in 2018**. The centre has benefited from a **strategic partnership** with Airbus, which has seen staff (Burnap and Morgan, from Psychology) seconded to the company to lead major research. This strategic partnership was recognised in 2017 with Airbus locating its only global **Centre of Excellence in Cyber Security Analytics** at Cardiff University (Director, Burnap).

The **Cardiff Centre for Artificial Intelligence, Robotics and Human Machine Systems (IROHMS)** (launched 2019, co-director Allen, theme leader Eslambolchilar, 12 FTE COMSC category A staff across all three research sections) is a collaboration with the schools of Engineering and Psychology, supported by £1.9m from the European Regional Development Fund (ERDF). Interdisciplinary groups target human-like AI, cyber systems and society, social robotics and explainable/ethical AI. IROHMS has increased our staff capacity in HCI (recruitment of Verdezoto, Stawarz, Fuentes and two research staff) and equipment to support research into social interaction with technology in healthcare and aging scenarios.

Hatelab (established 2018, Deputy Director Burnap) is a collaboration with the School of Social Sciences that has developed world-leading data science methods to detect, measure and counter the spread of hate on social media platforms. The lab has presented evidence to the Home Office select committee, and their activity has led to COMSC being the largest recipient of ESRC funding amongst all computer science departments in the UK in 2017/18 and 2018/19. Hatelab research has developed novel approaches to feature embeddings and fuzzy reasoning, able to identify the complex language used to express offensive and divisive language, generating impact through integration into UK police services to monitor and counter hate online.

1.6 Research integrity and open research

The School has a dedicated Research Ethics Committee (REC), which works aligned to Institutional requirements, informed by work of the University Open Research, Ethics and Integrity Committee (see Institutional statement). Staff must apply for approval for all applicable research

(e.g., involving collection and storage of personal data). Applications are reviewed by REC on a rolling basis to ensure compliance. Research integrity training is actively monitored, being compulsory for all academics and PGR students, and required prior to application to the REC or supervising undergraduate/postgraduate projects.

We are compliant with all funder requirements and the Concordat on Open Research Data. Output Open Access has been coordinated by a School champion and Research Manager, including staff training, recording and ensuring compliance (green or gold), and reporting. Post-prints of accepted publications are deposited to the Cardiff University's online repository, with datasets and software code also made open access through the University open data platform. All research-active staff have registered their ORCID in the Institutional research information management system, following Research England's recommendation. The School has followed all principles of the University's REF2021 Code of Practice, which focuses on inclusion, transparency and strong engagement with staff, led by the School's senior team, who undertook equality, diversity and inclusion training specifically aligned to their REF roles.

2. People

2.1 Equality and Diversity

The School received an **Athena Swan Bronze** award in 2015, successfully renewed in 2019. There are currently two ED&I coordinators in the School, including the chair of our Athena Swan Self-assessment Team (Jones). Progress against our successive Athena Swan action plans has led to a number of improvements in the research environment. A large focus has been placed on ensuring inclusive staff recruitment and promotion processes, with attention paid to the wording of adverts, guidelines for candidate presentations, mandatory unconscious bias training, and ensuring female representation on interview/promotion panels. Over the period these activities have contributed to a rise in the proportion of female staff recruited (33%), the total employed (28% compared to sector average of 22%) and promotions (24% of category A promotions were female). Changes to the process used to allocate School roles has seen an increase in female representation in our Senior Management Team (3 of 11) and School Board (3 of 14). The overall percentage of female PGR students has risen to 41% in the period (compared to sector average of 27%). The School recently secured £600k of HEFCW funding to support and scale-up our outreach in partnership with the Institute of Coding, which includes employing undergraduate student ambassadors on year-long placements to promote computer science to schoolchildren. We have six "Dignity and Wellbeing contacts", providing an opportunity for all staff to raise concerns informally or seek advice. All staff on probation are assigned an experienced mentor from within the School, while all staff have access to the University-wide mentor scheme (20 COMSC staff have joined the scheme as either mentor or mentee since REF2014).

We support flexible working for all staff where possible, for example, research-active staff may consolidate teaching duties in one semester to concentrate research time; home working is accommodated where appropriate, and flexibility is provided in working hours. Major School events and regular meetings are scheduled during core hours (10am to 4pm) to ensure that staff with caring responsibilities are able to participate. Following the move to predominately remote working due to COVID-19, guidance was developed in conjunction with our staff, including keeping one day per week clear of School committee/working group meetings to limit distractions, and a documented shared commitment to be mindful of individual circumstances. All research staff are invited to participate in School meetings and research/impact-related briefings, with equal opportunities to serve in administrative roles and on School committees. In 2019, we implemented a returners scheme to support staff following extended periods of leave, which reduces their allocated workload to enable them to target particular areas of their role. To date, one member of non-category A staff has taken advantage of the scheme on return from maternity leave.

2.2 Staffing and Recruitment Strategy

The School has considerably increased its critical mass since REF2014 with a strategy to predominately target the recruitment of **ECRs** across all three research sections, with a smaller number of more senior appointments to provide further **leadership and experience** in these areas. In total, 28 category A staff have joined, while 5.2 FTE have left (for example through retirement or to take up other academic/fellowship posts), resulting in 45.55 FTE category A staff

in our submission, with 23% female and 65% from 13 countries outside of the UK. Equality, diversity and nurturing talent have been key aspects of our recruitment process aimed to ensure the **long-term vitality of our research environment**.

To strengthen our future research growth and bring the balance between senior and junior staff in line with the sector national average (see below), 25 category A **lecturers** (7 female; 18 male) were appointed, with 20 of these taking up their first lectureships (7 female; 13 male). 9 of these staff were previously PDRAs within the School, demonstrating the success of our career development support to research staff.

3.5 FTE senior lecturer appointments (1 female; 2.5 male) have been made to provide **further leadership** in line with our strategy to invest in the three research sections. Y. Li was appointed as a focus for COMSC engagement with the DIRI. Eslambolchilar was our first appointment in HCI, which has directly led to the recruitment of four further staff in this area (Finnegan, Fuentes, Stawarz, Verdezoto). The appointment of S. Li strengthens capacity in Cybersecurity towards a standalone research section, adding complementary Digital Forensics expertise. A joint appointment (Mitra) between COMSC, the School of Mathematics and the UK Office for National Statistics was designed to increase collaboration in data science.

The University-wide Darlithwyr Disglair (Brilliant Lecturers) Scheme recruited two further staff to their first lecturing positions through a targeted 2-year training programme, as part of a 36+ interdisciplinary cohort. With the exception of these posts (Stawarz, Fuentes, since made open ended), all category A appointments during the period have been on full-time, open-ended contracts.

	Lecturer	Senior Lecturer	Reader	Professor
REF2014	9.4	3	1.5	10.8
REF2021	25	7.6	2.4	10.55

2.3 Staff development

All non-probation staff have an annual performance development review (PDR) with their line manager to reflect on progress, career development, and define their objectives for the coming year. Since 2015, all line managers undertake mandatory training to ensure high-quality support, aligned to enhancing successful personal development. The School's environment has contributed to 17 staff being successful in promotion applications since REF2014, with 6 promotions to professor (Allen, Burnap, Lai, Schockaert, Spasić, Taylor), 2 to Reader (Eslambolchilar, Mumford) and 9 to Senior Lecturer (Abdelmoty, Booth, Cerutti (since left), Corcoran, Langbein, Perera, Liu, Sun, Theodorakopoulos). As a signatory to the San Francisco Declaration on Research Assessment, journal-based metrics are not considered by the School promotions panel, with all cases assessed on assessed merits of the research (an approach also applied in our REF preparations in alignment with University expectations). In 2017, the University introduced a 5-day leadership training programme for newly-promoted professors, taken by two COMSC staff. One member of staff was successfully promoted to Professor after participating in the University's Academic Promotions Development Programme, designed to support career progression for Readers from underrepresented groups.

All staff can request School budget to **support equipment, seedcorn research and travel** (examples in Section 3.1), which are approved solely on their quality, opportunity for staff development and potential impact on the scope and culture of research. In particular, requests are not judged on seniority, current/past funding or track record, allowing staff at all stages of their career equal access to support to develop new areas, proposals and impact. The School has employed three additional members of professional support staff to assist academics with research proposal preparation, research project management and industry engagement.

Open to all staff, the University research leave scheme (REF5a) provided one year of study leave and travel funds, and supported five staff (Spasić, Lai, Rosin, Langbein, Preece) to develop their long-term research agendas, international collaborations and dissemination activity. For example, the scheme allowed Preece to commit time to develop international collaboration within the DAIS ITA programme (Section 2.4), resulting in his appointment as the UK academic lead. In 2019 the

Disglair ECR scheme was introduced to support research leave, which allowed Eslambolchilar time to develop a new collaboration with Architecture and Engineering on Human-Building Interaction for sustainability, safety and wellbeing.

Supporting early career staff. The support provided to ECRs reflects their importance to our strategy, with notable success in their transition to independent researchers. Of the 6 ECRs reported in our REF2014 environment submission, one secured a position at King's College London, while the five remaining have submitted eight successful promotion applications (three to professor), and raised their external profile (Burnap, AI Council member; Schockaert, European Association for Artificial Intelligence). Three are also now in senior leadership roles (COMSC research section leader, COMSC impact champion, DIRI co-director).

ECRs benefit from ringfenced time in the School's transparent workload allocation process and are allocated a senior academic mentor in addition to their line manager. **Training support for ECRs** includes dedicated away days for developing research ideas and applications, networking events, external career development workshops and opportunities to receive feedback from experienced researchers. ECRs and PDRAs are encouraged to apply for **personal fellowships**, and receive dedicated mentoring to develop their application, resulting in the award of the School's first UKRI Future Leader Fellowship in 2020 (Camacho-Collados). Other successes include the recruitment of a Marie Skłodowska-Curie Fellow within the Sêr Cymru II programme (Gutiérrez-Basulto) and an ERC starting grant (Schockaert). Our discipline-specific support complements the University's "Academic Practice" programme for ECRs during their initial 3-year probation period, which covers all aspects of career development, with ten optional research focussed courses, and leads to Fellowship of the Higher Education Academy (FHEA).

Continuing professional development. We are committed to staff training and development in accordance with the Investors in People framework. A comprehensive range of development courses is provided by the University, including workshops on PGR supervision, leadership, project management and performance management, including mandatory training (ED&I, Information Security, Research Integrity, Unconscious Bias). The School has funded the Aurora National Leadership Programme for nine female academic staff since REF2014. Six staff (Burnap, Cerutti, Corcoran, Schockaert, Theodorakopoulos, Spasić) have taken advantage of Cardiff Futures, the Vice-Chancellor's programme designed to help academic staff to develop their career paths and to contribute to shaping the future of the University. Following their participation, all six have been promoted, and five have taken on senior leadership roles within the School or external projects, with Cerutti leaving to take up a prestigious Rita Levi-Montalcini Research Fellowship at the University of Brescia. Research section leadership and other senior roles in the School are appointed for fixed 3-year periods with open calls, allowing all staff the opportunity to gain leadership experience.

2.4 Research students

Our PhD programme has significantly expanded between 2014-20. The total number of PGRs in progress has now grown to 61 (up 49% from 2014). To accommodate this expansion, the School has invested in refurbishment of our PhD offices over this REF period.

	14/15	15/16	16/17	17/18	18/19	19/20
<i>Applications</i>	164	161	146	140	255	210
Starters	11	12	19	11	24	22
<i>Enrolled total</i>	36	33	43	44	53	61

All aspects of PhD provision are overseen by the PGR Operations group, chaired by the Director of PGR studies (Marshall). This team also comprises a Deputy Director, three PGR admissions tutors (two handling general admissions, one specialising in international scholarships, e.g., China Scholarship Council), a dedicated lead on PGR training (Espinosa-Anke) and the chair of the PGR student reps, supported by the School Manager and an administrative assistant. PGR recruitment is covered at monthly meetings of the School's Admissions and Recruitment Group. Both groups report to the School Board and Senior Management Team.

COMSC is a founding partner in the international distributed analytics (DAIS ITA) programme established by the UK and US Governments (2016-2026). Funded by Dstl in the UK, the programme is designed to train PhD cohorts in a culture of collaborative working between UK and US academia, industry (IBM, Airbus, BAE Systems), and government. Since 2016 DAIS has funded 12 studentships in COMSC. Every DAIS PGR benefits from regular bespoke training events alternating between UK and US venues, including an intensive research "boot camp" and an annual meeting to present their work to external stakeholders through posters, papers and live software demos.

In 2018-19, a consortium between Supercomputing Wales (Section 3.2) and Bristol University was awarded the £5.4m UKRI **Centre for Doctoral Training in Artificial Intelligence, Machine Learning and Advanced Computing**, in which COMSC is a partner. Students in the CDT benefit from extensive training and networking opportunities with an interdisciplinary cohort across Wales, including external placements, residential sessions, guidance on socially responsible innovation, and taught components and practical workshops on HPC delivered in partnership with Supercomputing Wales' facilities (Section 3.2).

In 2020, the University awarded the CCSR an **Interdisciplinary Doctoral Training Hub in Cyber Security Analytics** (EPSRC-DTP funded), in collaboration with Psychology and Social Sciences. The hub focuses on the fusion of AI, cybersecurity and risk, considering implications of emerging technologies from both a human and algorithmic perspective. An interdisciplinary training programme will equip students to develop and communicate solutions to cybersecurity challenges from technical, human factors and social perspectives. The first cohort of 5 students will commence in 2021.

Recruitment: PGRs are recruited from diverse backgrounds, including part-time applicants working in industry (IBM, Airbus, Esys). The 19/20 cohort comprises 36% UK, 11% EU, and 53% international students. After an initial interview with the prospective supervisor, all applicants are interviewed by a panel of two staff to ensure they have the potential to undertake PhD study, irrespective of the funding source. In addition to the centres described above, funding sources include China Scholarship Council, School/University scholarships and industry (in 2020 IBM spent 25% of their EPSRC iCASE allowance with the School). The School has also been active in receiving international exchange PGRs from other institutions and through participation in Marie Curie networks, producing REF outputs such as automatic semantic modelling of indoor scenes (Lai, Martin, *ACM TOG*), robust virtual unrolling of unopenable parchment X-ray microtomography images (Rosin, Lai, *IEEE TIP*). Since 2018, we have funded a number of Teaching Associate positions combining a part-time PhD with a 0.5 FTE teaching support role.

We participate in the Cardiff Undergraduate Research Opportunities Programme (CUROP, see Institutional statement) and IAESTE, which fund undergraduates to work with academic staff during the summer on research programmes, helping to attract potential PGRs and give them a taste of research. Over 30 students have taken advantage of these in COMSC, with several going on to begin PhD study at Cardiff. Turner is an example of the long-term success of this approach, whose participation in CUROP in 2012 led to the award of a PhD, researcher and finally lectureship positions within the School.

Skills development and support: All PGRs have a primary and secondary supervisor in COMSC, with 9.3% also having a supervisor from another discipline. Postgraduate students have the opportunity to gain appropriate teaching experience, including guest lectures on their research areas. Two PGR events take place each year to develop skills in communicating and defending their work. In January, each student presents a poster based on their progress, and an oral presentation to staff and peers at a "research retreat". This includes external speakers (e.g. from GoogleX, IBM) to provide insight into future career development. In addition, PGR students are encouraged and supported in developing their own research culture, including a student-led seminar series.

In addition to a standard equipment budget of £1,600 per PGR, funds are available for all students to attend relevant international conferences and workshops (examples include ICML, IEEE VR, AAAI and CVPR) during their studies. The School has spent an average of £63,147 per annum in supporting staff and PGR conference attendance (conference registration plus travel).

Training is overseen by the PGR training officer, with a variety of in-house training courses based on demand, and students can request external training where needed, including international summer schools and certification courses. General research and transferable skills (e.g. time management, statistics) and career development training are provided by the Doctoral Academy (see institutional statement), which also fosters a PGR community across the University through interdisciplinary events.

Monitoring and feedback: We have carefully designed, implemented and audited quality procedures for **progress monitoring** of PGRs (aligned to the expectations of the University). Students undergo an end-of-year review (at 9, 21, and 33 months), submitting a detailed progress report (or research paper), with feedback from the lead supervisor, assessed by a panel of two independent assessors. Progression is subject to successful completion of these reviews, with panels able to request remedial action where necessary. Supervisors conduct light touch reviews in between to identify training needs or other issues. Students receive formative feedback from a wide range of academic staff across all research sections at the annual poster day and research retreat. Students are expected to meet with their supervisors on a weekly or bi-weekly basis and are required to keep meeting records.

We implement several, complementary mechanisms for cohort feedback to ensure that PGRs have an impact on future PGR activities and that any issues can be triaged and resolved quickly. Two student reps are elected by their peers for each year of the programme, meeting with the PGR Operations team formally every semester as part of a student-staff panel. Between these the PGR student reps are approached on an ad-hoc basis for ideas and feedback on plans for upcoming events and policy changes, supplemented by regular open 'forums' for all PGRs. While the supervisory team is usually the first port of call for any individual circumstances affecting a student's study, the DPGR and Deputy DPGR operate an open-door policy allowing students to raise issues that are sensitive or relate to supervision. While PGRs naturally establish peer-support networks through research groups, office neighbours, and university societies, we have recently launched a near-peer mentoring programme in response to the COVID-19 pandemic to help new starters engage into the peer-support aspects of the School's research culture.

3. Income, infrastructure and facilities

3.1 Research income generation

During the period, our research income has totalled £15.0m (compared to £10.4m for REF2014), including 51 UKRI Research Council grants, 24 EU funded grants and 26 from industry. The School encourages investigators to exploit a wide diversity of funding sources, reflected in 28% of research income from Research Councils (EPSRC, ESRC, AHRC), 25% from the EU, 22% from UK government bodies and 18% from UK Industry. Significant grant awards include formal lexically informed logics (ERC Starting Grant, Schockaert, >£1m), which led to substantial growth in the area of AI in COMSC; Social Data Science Lab, Centre for Cyberhate Research & Policy (ESRC, Burnap, £1.37M COMSC share), which started 7 years of continuous funding in collaboration with Social Sciences; and Seeing the Future (EPSRC, Marshall) continues a fruitful collaboration with Psychology.

The three principal actions of our REF2014 strategy (Section 1.2) are evident in our portfolio. 54% of projects involve **cross-discipline collaboration** with other Schools and world-wide institutions, including the Centre for Cyberhate Research & Policy: Real-time scalable methods and infrastructure for modelling the spread of cyberhate on social media (with Social Sciences, £1.54m), DAIS ITA (with Social Sciences, £1.9m), Centre for Cyber Security Analytics (with Psychology, Law & Politics, £8m). The School received the highest level of funding from ESRC to any UK Computer Science department in 17/18 and 18/19 with a total value of £550K. **Strategic partnerships** have resulted in sustained funding from Airbus (£1.1m) and IBM (£1.9m). Over the period we were awarded five Knowledge Transfer Partnerships (Admiral, Equiniti, ActiveQuote, Airbus, Orbital Media) and launched the Data Innovation Accelerator (£3.5m, WEFO). Industrial partners on externally-funded projects from fields including engineering (Bae & Renishaw), law (Muckle), financial services (Simudyne) and aerospace (Airbus) have provided substantial in-kind support such as staff time, workshops, facilities and computation/simulation time.

Projects such as *Social Data Science Lab: Methods and Infrastructure Development for Open Data Analytics in Social Research* (ESRC) and *Lost Visions: retrieving the visual element of printed books from the nineteenth century* (AHRC) result from our leadership and participation in **larger University research initiatives**. We have been very successful in exploiting small grant funding to kick start new areas or interdisciplinary collaborations. This includes internal and external funding to support summer undergraduate research projects and internal seed corn funding from the DIRI. As an example, a collaboration with the School of Medicine on computational approaches to lipidomics started from a CUROP internship (Section 2.4) and led to COMSC participation in an ERC-funded project and joint outputs (*Bioinformatics*, *Cell Metabolism*). These schemes particularly support ECR staff to explore early ideas in advance of larger grant applications and gain their first experience of research supervision.

Supporting our researchers: Our support for grant applicants has resulted in a 31% success rate over the past 4 years (97 out of 309 applications). Staff's long-term strategy for research proposals are discussed and prioritised during the PDR process to identify support needs, with applicants assigned an internal reviewer/mentor at an early stage.

We allocate an average of £109,322 per year to PhD scholarships, £83,155 on support staff for bid preparation, costing and submission, and match-funding on grants. We spend an average of £153,837 annually to support staff travel, equipment, visitors, collaboration, seminars, away days, public engagement, and other research-related activities. For example, the VC section requested an £18k investment in a mobile eye tracking system in 2018, which supported one interdisciplinary PGR project (Liu, *IEEE Access*), three grant awards, and a visiting fellowship funded by the German Research Foundation (Liu, *ICIP conference*). This spend has grown substantially since REF2014, reflecting the strategic approach taken by the School to its increasing level of research activities during this REF period.

3.2 Infrastructure and facilities

In Autumn 2021, the School will move with the School of Mathematics into **Abacws**, a new 9,700 m² purpose-designed building which will accommodate further growth and support the strategic vision described in Section 1.2. The strategic investment of £39m from the University recognises the substantial growth achieved since REF2014 and solidifies the close relationship between COMSC and Mathematics in areas such as data science and machine learning, exemplified through co-leadership of the DIRI (Section 1.5). Abacws has been designed to facilitate formal and informal interaction between disciplines and will place us at the heart of the University estate, providing an opportunity to further develop our interdisciplinary ambition.

The School has occupied the current site, shared with Engineering and Physics, since 1995, where the combination of strategic investment in staff coupled with space constraints has seen COMSC spread over three buildings. Abacws offers modern infrastructure and facilities on a single site, substantially increasing our physical footprint, providing a much-needed increase in contiguous space and giving our research groups new freedom to develop research culture and build identity. Abacws will have additional lab space to support growing practical research in areas such as HCI, IoT and Cybersecurity and importantly, to allow interaction with Mathematics to flourish. All staff in Abacws will have individual offices, with a range of informal collaboration spaces on each floor. PGR students and PDRAs will be co-located thematically in rooms of at most six people, allowing greater opportunity for interaction and informal mentoring. Staff and students will share access to dedicated labs with state-of-the-art infrastructure including the Cyber Range, social robots and motion capture facilities, to support their involvement in the delivery of our strategic objectives and growth of research sections.

In addition to the forthcoming new building, during the REF period, over £2.4m has been invested in refurbishing our estate for teaching, research and engagement, including new flexible collaborative facilities used for research events, industry collaboration, outreach and engagement.

The School makes extensive use of **Advanced Research Computing @ Cardiff (ARCCA)**, which provides **high performance computing**. The University has invested substantially in ARCCA during this REF period, which is one of the largest and most efficient academic supercomputer facilities in the UK. It comprises a pre-existing cluster of 2048 Intel processors with an additional 864 cores for high throughput, with a new Linux cluster consisting of 7,000 cores with an additional

1040 cores for performance acceleration. The School has funded additional GPU nodes exclusively for our students and staff, which are heavily used for deep learning applications by the VC section. Overall, COMSC staff and students have utilised over 3m core hours from ARCCA, for example, to train word embeddings, knowledge representation and reasoning, and deep learning in advanced AI and Cybersecurity, reasoning via inducing semantic relations from conceptual spaces (Schockaert, *Artificial Intelligence*), performance analysis of social comparison-based relaying for device-to-device communications (Whitaker, Allen, *IEEE TWC*).

The ARCCA facilities are augmented by **Supercomputing Wales**, a £16m programme (jointly with Swansea, Bangor and Aberystwyth Universities, part funded by ERDF) whose Academic Director (Whitaker) and management team are based in COMSC. Since 2017, Supercomputing Wales has supported the HPC facilities refresh in ARCCA and six full-time RSEs at Cardiff University including one embedded within COMSC (supporting evolutionary simulation and intelligence research in collaboration with IBM and Dstl) and a specialised technical support team providing wrap-around services.

The **Research Centres and Institutes** that the School both participates in and leads (Section 4.1) provide an active, challenge-led environment to support multidisciplinary research and impact creation via unique infrastructure:

The **Centre for Cyber Security Research** recently established a cyber-physical testbed and immersive visualisation capability. Supported by a £1.2m HEFCW investment, this includes a scalable virtualised cyber range with the ability to build “digital twins” of future IT/IoT environments, identify their vulnerability to cyber-attack, and evaluate cyber detection and response algorithms within a realistic environment. The testbed also includes several physical components, such as those controlling smart city, transportation, and manufacturing infrastructure, to conduct similar research in the context of critical national infrastructure. The investment was strategically scoped to complement local facilities, including the energy and autonomous vehicle testbed at Thales National Digital Exploitation Centre (NDEC) and the manufacturing testbed at Airbus to enable co-creation of research challenges and co-location of researchers across sites to support research impact (e.g. EPSRC project on safety critical system security).

The **Crime and Security Research Institute** features substantial space for hot-desking with external partners (e.g., Airbus, Dstl, IBM, UK police forces) as well as flexible formal and informal meeting space. The Institute is scheduled to move into the University's new Innovation Campus 'sparc' building in late 2021, where it will benefit from a purpose-built secure data facility allowing researchers to work with data at a high level of security classification, as well as a data visualisation suite inspired by IBM's THINKLab model, and a 'TEDx' style theatre for workshops and conferences. As a focal point for co-working between the University and external partners, Sparc offers great potential for COMSC to deliver against our future objectives for impact and funding applications in computational science, AI/ML and human-computer synergy.

The **Human Factors Technology Research Centre** (joint with Engineering and Psychology) provides a laboratory to investigate aspects of human communication and interaction through imaging, video, audio, and motion capture, including an upgraded 3dMD 4D (dynamic 3D) camera system, handheld 3D scanners, motion capture systems (Phasespace, Ascension MotionStar, Polhemus LIBERTY), eye trackers, hand gesture trackers, and audio-video recording facilities. It has strong internal interdisciplinary links with Medicine, Dentistry, Optometry, Social Science and CUBRIC, and, externally with Renishaw Plc, British Aerospace, Airbus and General Dynamics. For example, collaboration with Dentistry and CSI has developed video surveillance techniques and new models of crowd behaviour with policing applications.

In addition to University-wide IT support, the School has four (4 FTE) dedicated staff onsite from the University IT service, who manage a range of in-house research support services and software, such as ShareLaTeX, OpenStack, Matlab. We fund a School workshop with 1 FTE support (for example, to develop and assemble hardware for IoT research) and two software engineers to maintain and support usage of the cyber range infrastructure.

Access to scholarly literature is provided on-site through the **Trevithick Library**, supported by a dedicated subject librarian, with specialist information resources including ACM Digital Library, British Standards Online, MathSciNet database, IEEE Xplore, and the Safari ebooks collection.

3.3 Support for Impact Creation

At a strategic level, the School has an impact champion (Burnap) who actively promotes research that leads to impact. The School's Industry and External Engagement Manager further supports this agenda, by proactively approaching industry and maintaining key relationships, including KTPs (Admiral, Equiniti, Airbus, ActiveQuote, Orbital Media), CASE studentships (e.g. Admiral, BAe, Renishaw) and increasing our overall outreach and dissemination activities. Further support from the University's Business Engagement & Partnership Team has been instrumental in realising impact with key partners and exploiting new opportunities designed to deliver future impact cases. A 0.5 FTE Impact Officer has been employed during the REF period to help track impact, and work with the substantial support provided by the University for all researchers working in the innovation and impact space (see REF5a). The University Commercial Development team provides central support with issues around IP and licensing.

Potential avenues to impact are explored with all staff at annual Performance Development Reviews, to identify opportunities and support needs. The School's External Advisory Board also plays an important role in guiding our impact strategy and activities. External members represent Google, Microsoft, BT, Airbus, ONS and CapGemini with regular sessions scheduled for staff from each section to showcase emerging research with potential for future impact. The Data Innovation Accelerator (Section 4.2) provides a mechanism for impact generation with South Wales SMEs.

During the period, the School has launched two new academies addressing skills and innovation, the National Software Academy and the Data Science Academy. Both share an innovative model of delivery where students frequently interact with visiting industry and external stakeholders, through guest lectures and by working on real world projects. In addition to underpinning our sustainable growth (Section 2), the academies have been instrumental in building sizeable industry networks enabling connections from teaching to translate into benefits for research and impact. For example, a KTP project with a local insurance company (Y. Li, ActiveQuote) resulted from an initial visit to meet undergraduate Software Engineering students.

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

4.1 Research collaborations, networks and partnerships

Academic staff have engaged in collaborations with over 100 UK and international academic partners including MIT (USA), University of South California (USA), KU Leuven (Belgium), National University of Singapore, Tsinghua University (China), resulting in more than 200 co-authored outputs with researchers in these universities. Our REF-submitted outputs involve collaborators from 134 institutions in 30 countries. Over 10 collaborative partnerships have been undertaken with industry and other organisations (Sections 3.2, 3.3) including IBM UK/US/Europe, Airbus, Spanish Royal Academy.

The School has extensive collaborations with **research institutions in China**, including Tsinghua University, Chinese Academy of Sciences, Nankai University, University of Science and Technology of China, funded by EPSRC, the Royal Society, the British Council, and Natural Science Foundation of China. This has resulted in over 30 joint publications in journals and conferences. We have strengthened our strong partnership with **Tsinghua University**, not only resulting in a strong profile of collaborative publications, but also deeper collaborations such as joint PhD supervisions and impact creation. For example, Lai has a joint Royal Society-Newton Advanced Fellowship grant (2016-2020) with Liu at Tsinghua, supporting collaborative research, capacity building, joint PhD supervision and bilateral visits. In collaboration with Hu through the Tsinghua-Tencent lab, Tencent has exploited Lai's research in their "Map & StreetView" product which has over six billion daily uses, leading to a REF impact case. Other members of staff (Rosin, Marshall, Liu, Wu) collaborated with Tsinghua on research during this REF period and one former member of senior staff (Hu) held a joint position with Tsinghua.

The School has developed long-term collaborations with **US institutions** that have been continuously funded (£1.9m) since 2007 via the joint US/UK International Technology Alliance

(ITA) model established by the US Army Research Laboratory and UK Defence Science Technology Laboratory (Section 2.3). Our key US partners in these collaborations include IBM US, Penn State, UCLA, UMass, and Yale. One member of senior staff (Taylor) holds a part-time position with Notre Dame which has benefited one of our impact case studies concerning the application of Blockchain through access to US industry and government, while facilitating new transatlantic collaborations for other staff across the University.

Staff are encouraged to invite external academics for **collaboration visits** and the School has hosted over 20 international visitors since REF2014 from institutes including the University of Tokyo, University of A Coruña, Washington University at St Louis. Outward visits have been supported by the British Council, Royal Society, EPSRC and University mobility grants to over 20 leading research units in the world including Yale University, the University of Bremen, University of Waterloo, TU Delft and the Chinese Academy of Sciences.

As detailed in Section 1.5, the School has also played a leading role in several multidisciplinary Centres and Institutes. In addition, staff have contributed to a wide range of other Cardiff University centres, including the Systems Immunity Research Institute, Water Research Institute, and Danau Girang Field Centre in Malaysia.

4.2 Interactions with key research users, beneficiaries or audiences

As highlighted above, external users play a significant role in shaping and co-creating research across all research sections. Further noteworthy examples include:

The **Data Innovation Accelerator** (DIA, Whitaker, Burnap) is a £3.5m investment by the ERDF and Cardiff University to support development of our innovation agenda and reach a wider range of potential beneficiaries. The project funds a team of Data Scientists to support collaborative projects between COMSC, SMEs and other organisations. The DIA allows our staff to quickly engage in the impact agenda and exploit their expertise for the mutual benefit of staff, School engagement and external companies, and is particularly well suited to enabling ECRs to develop their first industrial links. Since its inception in 2017, COMSC staff have engaged with collaborative projects, with examples ranging from synthetic data generation for testing financial credit scoring (Theodorakopoulos, W2 Global Data) through to image and text recognition for price comparison (Lai, Avoir Fashion).

The **Centre for Cyber Security Research** has developed strong working relationships and research funding with Airbus, Aston Martin, BAE Systems, BT, Thales and Toshiba, submitting research funding applications with all partners. The Airbus relationship has been particularly successful, with an initial part-time secondment (Burnap) leading to £4.9m of external funding in a research programme including two academics, two research staff and three PGR spending time embedded with Airbus. A similar secondment (Reinecke) commenced in 2020 with Thales at NDEC, working on critical national infrastructure security. The Centre leads the safety critical systems theme of the National Centre of Excellence for IoT Systems Cybersecurity (PETRAS), a £14m EPSRC centre, and is a core member of the EPSRC Research Institute for Trustworthy Interconnected Cyber-Physical Systems (RITICS).

The recent partnership with the **ONS** has led to a jointly-funded Senior Lecturer appointment with COMSC and Mathematics in 2020, to build new research collaborations that improve understanding on topics such as healthy ageing, economic intelligence and education and skills. The scope of the partnership will be expanded as we move into Abacws, taking a holistic approach combining skills development (through our teaching academies), research and impact.

In addition to secondment, staff are supported to engage beneficiaries through personal consultancy and participation in spin out companies. Staff are encouraged and supported in engaging the general public in research. For example, in 2015, the SHERLOCK natural language crowdsourcing game (Preece, *IEEE THMS*) engaged a general public audience as part of the BBC's national "Make it Digital" tour, and in 2018, the CSRI Sentinel platform (Preece, *IEEE TCSS*) was used to support the "Let's solve litter in Grangetown" challenge involving groups of young people from a diverse Cardiff community.

4.3 Wider contributions to economy and society

In addition to the impact cases included in the REF impact submission, other examples in progress include data analysis of pedestrian footfall to support sustainability of the high street (Mumford, Ministry of Housing, Communities and Local Gov.), recovery of content from damaged historical scrolls (Rosin, *Scientific Reports*), detection of fake police reports (Camacho-Collados, Liberatore, *Knowledge Based Systems*), information extraction from narrative reports describing MRI scans of the knee to support physiotherapy self-care for knee conditions (Spasić, *JMIR Research Protocols*), HateLab: using AI to stem online hate speech (Burnap, *British Journal of Criminology*), open source intelligence analysis to understand community tensions and conflict (Preece, *British Journal of Criminology*).

The School has built strong collaborations with other disciplines facing new computational challenges, leading to new capability, innovation and impact. Within the University, examples include Medicine (Searching and statistical analysis for lipidomics, *Bioinformatics*); Mathematics (Multiple domination models for placement of electric vehicle charging stations in road networks, *Computers & Operations Research*), Healthcare Science (Using routine referral data for patients with knee and hip pain to improve access to specialist care, *BMC Musculoskeletal Disorders*), Dentistry (Detecting violent and abnormal crowd activity using temporal analysis of grey level co-occurrence matrix (GLCM)-based texture measures, *Machine Vision and Applications*), Engineering (Management of collaborative BIM data by federating distributed BIM models, *Journal of Computing in Civil Engineering*), Psychology (Timing rather than user traits mediates mood sampling on smartphones, *BMC Research Notes*), and Social Sciences (Tweeting the terror: modelling the social media reaction to the Woolwich terrorist attack, *Social Network Analysis and Mining*). Our future strategy (Section 1.3) will further consolidate our critical contributions to research and impact at Cardiff via these strong interdisciplinary partnerships.

4.4 Esteem and evidence of success of research leadership

The esteem and visibility of the School has increased substantially during this REF period, with members of staff actively serving and taking leadership roles in their research community. Evidence of the success of our academic leadership includes editing key journals, chairing major conferences, extensive advisory activities, invitations to give prestigious keynotes, and best paper awards (ECRs during the period underlined).

Prizes, awards and other distinctions: As a result of the School's collaboration with Tsinghua University, Martin (now Emeritus Professor) received the Friendship Award, the highest award of China for "foreign experts who have made outstanding contributions to the country's economic and social progress". Taylor has been named by ICO Alert as one of 40 most influential researchers in the world in Blockchain. Rosin was made a Fellow of the International Association of Pattern Recognition. Rana and Burnap received the ACM Web Science Conference 2017 best paper award. Recognition for ECRs includes an honourable mention at ACM CHI (Stawarz), TAROS 2018 best paper award (Wu), Spanish Police Foundation Research Awards 2017 (Liberatore, Camacho-Collados), distinguished PC member at IJCAI (Polberg).

Appointments on advisory boards and committees: UK Government AI Council (Burnap); RCUK Digital Economy Programme Advisory Board (Preece); Ministry of Defence Independent Science & Technology Advisory Register (Preece); EPSRC Programme Advisory Board (Preece); testimony to Commons Home Select Committee (Burnap); Academic Council for Discovery Partners Institute, Chicago (Rana); Pakistan National Centre for Big Data and Cloud Computing Advisory Board (Rana).

Leadership roles: UK academic lead for the DAIS ITA programme (Preece); Treasurer of the European Association for Artificial Intelligence (Schockaert); Academic Director of Supercomputing Wales (Whitaker); Secretary of the Knowledge Representation and Reasoning Working Group of IFIP Technical Committee on Artificial Intelligence (Polberg).

Senior editorial positions: **Editor:** Computer Physics Communications (Walker); Concurrency and Computation Practice and Experience (Walker); **Associate editor:** IEEE Transactions on Multimedia (Liu); IEEE Transactions on Human-Machine Systems (Liu); ACM TAAS (Rana); IEEE TCC (Rana); ACM Transactions on Spatial Algorithms and Systems (Jones); ACM Transactions

on Internet Technology (Rana); IEEE Transactions on Parallel and Distributed Systems (Associate editor: Rana); Social Network Analysis and Mining (Whitaker); IEEE Transactions on Information Forensics & Security (Theodorakopoulos); **Editorial board:** Computer Graphics Forum (Lai, Rosin); Artificial Intelligence (Schockaert); Geoinformatica (Jones); Proceedings of the Royal Society A (Allen); Concurrency and Computation: Practice and Experience (Rana); IEEE Cloud Computing Magazine (Rana); Online Social Networks and Media (Whitaker); Wireless Networks (Whitaker); Argument & Computation (Caminada); **Area editor:** Computer Communications (Allen); Fuzzy Sets and Systems (Schockaert).

Conference organisation: British Machine Vision Conference 2019 (Co-chair: Sidorov; Programme chair: Marshall); International Conference on Computational Visual Media 2016 (Conference chair: Lai); Eurographics Symposium on Geometry Processing 2014 (Conference chair: Lai); UK Workshop on Computational Intelligence 2017 (Conference chair: Schockaert); RuleML+RR 2020 (Programme co-chair: Gutiérrez-Basulto); Scalable Uncertainty Management 2016 (Programme co-chair: Schockaert); Pacific Rim Conference on Artificial Intelligence 2016 (Programme chair: Booth); ACM CHI (Associate Editors: Finnegan, Fuentes, Stawarz, Turner, Verdezoto); CSCW (Associate Editor: Turner). 2015 Conference on Decision and Game Theory for Security (Programme Chair: Theodorakopoulos). ECRs are also active in organising workshops, e.g., London Argumentation Forum 2019 (Polberg); IJCAI 2019 workshop on Semantic Deep Learning – SemDeep (Espinosa-Anke, Camacho-Collados); ECSCW 2019 co-chair for Workshops and Masterclasses (Verdezoto).