Institution: University of Sheffield

Unit of Assessment: B-11 Computer Science and Informatics

1. Unit context and structure, research and impact strategy

1.1 Overview

The Department of Computer Science is committed to advancing the theoretical foundations of computer science and to achieving impact through close collaboration with end users. Our focus on interdisciplinary research is distinctive: much of our most impactful work arises from research at the boundaries between computer science and other disciplines. We play a central role in the University research environment, providing leadership for six interdisciplinary centres and flagship institutes.

Our vision is to address major challenges within four themes: *speech and language*, *healthcare technologies*, *bioinspired machine intelligence*, and *dependable and secure systems*. Our strategy is to develop a large cohort of excellent researchers that exhibit breadth as well as depth, enabling us to forge international collaborations that advance the discipline and create real-world impact. Work across our four themes spans novel contributions to the theoretical foundations of the discipline through to the translation of our research into applications used by thousands of people. Research activity is supported by substantial investment in computing facilities and infrastructure, including a planned £10.5m refurbishment of our accommodation.

Key achievements since REF2014 include:

- Growth in academic staff from 33 to 55, with a 100% increase in the number of female academics and 67% growth in international academic staff.

- Publications in top computer science (e.g. ACM, IEEE, TCS, NeurIPS) and interdisciplinary (e.g. Nature Communications, Nature Neuroscience, PNAS) venues.

- £32.5m in research income, a 73% increase from REF2014.

- Growth in industrial income from £875k to £2.1m, including two new industry-funded research centres supported by £1.4m to date.

- New groups in Algorithms and Security of Advanced Systems, the latter with a £1.2m strategic investment from the University.

- Growth in the PhD student population of 20%, with sustainability ensured through the award of a £5.2m UKRI Centre for Doctoral Training (CDT) award, further supported by £2.2m in industry-funded studentships.

- A successful impact pipeline that has produced three spin-out companies, informed UNESCO's COVID-19 response and added $120m to the value of a major Silicon Valley speech technology company.

We take great pride in being a collegial, supportive research community, one in which equality, diversity and inclusion (EDI) are core values. The Department was awarded an Athena SWAN Silver award in 2016. Through an ongoing action plan, we are committed to advancing EDI in the discipline through local, national, and international initiatives.

1.2 Unit structure, research strategy and progress towards REF2014 objectives

Our research strategy focuses on key questions and major challenges associated with our four themes. Research in each theme is supported by a cluster of research groups, each of which is led by a senior academic (Figure 1). Every theme addresses both fundamental research and engineering applications. Academic membership in these research groups is not exclusive; many researchers contribute to the activities of more than one group, and groups contribute to more than one theme.

The Department sits within the Faculty of Engineering. All groups are supported by specialist laboratory facilities, interdisciplinary facilities provided by the Faculty, and University-level high-performance computing (HPC). Our Research Software Engineering (RSE) group provides expertise on HPC within the Department and across the whole University.

In REF2014 we set out an ambitious plan for expansion, aiming to develop areas of existing strength (speech and language technologies, machine learning (ML), healthcare technologies) and grow our expertise in algorithms. Implementation of our REF2014 plans was further informed by a strategic review in 2015/16, which recommended that new groups be established in Algorithms and Security of Advanced Systems. The outcome over the assessment period has been a significant strengthening of our research across all four themes, as outlined below.
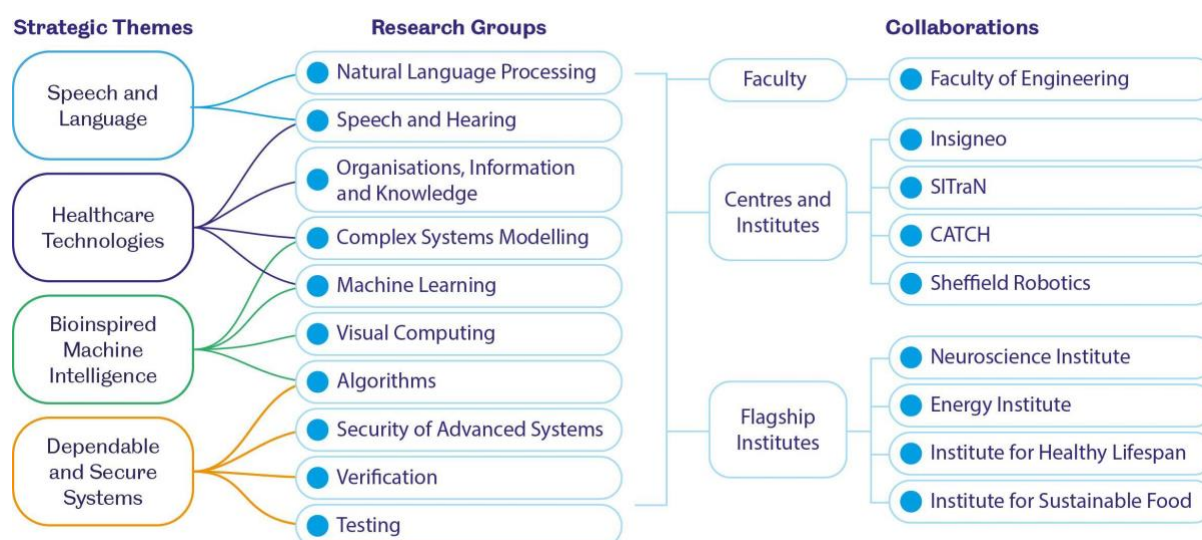

Figure 1: Key strategic themes, structure, and collaborations

Speech and language

A major challenge for spoken language technology (SLT) is to develop conversational agents that can engage in human-like dialogues: this requires a deep understanding of spoken language behaviour and robustness to the presence of multiple talkers. Explainability, trustworthiness and elimination of bias in SLT systems are also fundamental concerns.

We address these challenges through one of the strongest concentrations of SLT researchers in academia worldwide, comprising 18 academics from our *Natural Language Processing* (NLP) and *Speech and Hearing* (SPandH) groups (8 professors, 9 lecturers/ senior lecturers, 1 fellow). The cluster is unique in its ability to conduct research across a broad spectrum, from computational models of language and human hearing, to commercially deployed automatic speech recognition (ASR) and text engineering systems.

Our success in addressing the challenges of this theme is illustrated by influential publications. Work on noise-robust ASR includes an approach to using multiple microphones cited in Google patents (*Hain* ICASSP), and papers on the CHiME challenges for distant microphone ASR that have received over 1,000 citations (*Barker,* Computer Speech & Language). Papers published in top NLP venues cover social media analysis (*Aletras,* ACL), metaphor identification (*Lin,* ACL), idiomaticity detection (*Villavicencio*, ACL) and the evaluation of neural sentence encoders (*Barrault,* EMNLP). The latter has been cited over 1100 times and inspired the widely used GLUE benchmark. A study on predicting judicial decisions (*Aletras*, PeerJ CS) has received over 300 citations since 2016.

This theme was supported by funding awards totalling £16.3m. Additionally, we have ensured future sustainability through a £5.2m UKRI CDT award in Speech and Language Technologies, matched by £2.2m of industry sponsorship from Apple, Amazon, 3M and others. Three impact case studies have emerged from this theme. The Silicon Valley company VoiceBase established a centre to support *Hain's* world-leading research on ASR (£500k p.a.). Machine translation research has been supported by a prestigious £1.2m ERC starting grant (*Specia*) and has informed technology used by Facebook and Microsoft. Text engineering for social media analysis (*Bontcheva*) has been an outstanding success, attracting nearly £4m of grant funding and being used by Buzzfeed and Nesta.

Moving forward, a particular focus will be on SLT for low-resource languages and sparse data domains that are poorly served by current deep learning methods. We plan to establish a centre of excellence in NLP for computational social science.

Healthcare technologies

Research in this theme is driven by the complexity of the clinical setting, aligned with challenges in harnessing technology to deliver healthcare more effectively. We focus on computational models as tools to identify causal relationships in disease mechanisms. Key challenges include maximising the information gained from images and measurements, developing personalised models to improve diagnosis and target therapy, monitoring disease progression via data analytics, and translating these tools into routine use.

This theme is primarily supported by our *Organisations, Information and Knowledge* (OAK) and *Complex Systems Modelling* (CSM) groups, with input from the ML group. Fifteen academics contribute to the theme (5 professors, 10 lecturers/ senior lecturers). It is further supported by a network of clinical and interdisciplinary collaborations provided by Insigneo (the Institute for *in silico* Medicine), the Centre for Assistive Technology and Connected Healthcare (CATCH), the Sheffield Institute for Translational Neuroscience (SITraN) and the flagship Neuroscience and Healthy Lifespan Institutes.

Contributions to basic science and optimising therapy include insight into the mechanisms of wound healing from multiscale models of cells and tissue (*Walker*, J Roy Soc Interface), novel personalised models of the heart (*Clayton*, Phil Trans Roy Soc A), and models and risk stratification of intracranial aneurysms (*Watton*, Biomech and Model Mechanobiol). Examples of research translation include the integration of *Watton's* aneurysm growth model into the ITIS (Switzerland) SIM4LIFE software and clinical testing of a speech analytics system for the detection of cognitive decline (*Christensen*). Data analytics approaches have been used to understand patient trajectories through the NHS (PathAnalyse, funded by the Health Foundation and deployed in Sheffield Teaching Hospitals, *Villa-Uriol*) and to quantify physical activity in the community setting via a smartphone app (*Large-Scale Data* case study, over 1m downloads by 2019*).*

Grants totalling £5m were secured from funders including BBSRC, British Heart Foundation, the EU, NIHR, the Health Foundation, Rosetrees Trust, Wellcome Trust, Amazon and EPSRC. Many grants are collaborations between academic and clinical partners in the UK and internationally, as well as industrial partners, e.g. we are partners in the €10.3m PRIMAGE Horizon 2020 project.

Our future research focus will be on leveraging our expertise in ML in areas such as uncertainty quantification for personalised disease models and medical image analysis.

Bioinspired machine intelligence

Research is driven by the design of energy-efficient algorithms that learn from fewer data, and yield solutions that are interpretable and explainable. We tackle these challenges through fundamental research mainly inspired by biological organisms.

This theme is supported by 14 academics (3 professors, 11 lecturers/ senior lecturers) across the ML, CSM, *Visual Computing* and *Algorithms* groups and makes a substantial contribution to *Sheffield Robotics* (*Prescott* is the Director). Research spans fundamental theory on graph networks, genetic algorithms and reinforcement learning to applications, e.g. in cognitive robotics.

Highlights include work on graph clustering (*Peng,* STOC) described as "breakthrough" by ACM Fellow Sanjeev Khanna, work on graph convolutional networks (*Lu*, CIKM) that outperforms state-of-the-art models, and a novel energy-based formulation of learning for spiking neural networks (*Gilra*, ICML; e-Life). Models of insect navigation and learning (*Marshall*, *Mangan*, *Vasilaki*, PLOS Computational Biology) and their applications in robotics have provided the intellectual foundation for a spin-out company, Opteran. *Alvarez's* work on data-efficient latent force models for reinforcement learning (IEEE TAC) led to EPSRC funding on "one-shot learning". *Oliveto* and *Sudholt's* runtime analysis of genetic algorithms won a GECCO'14 best paper award.

The theme is supported by grants totalling £8.6m, including funding from Amazon (*Lu*) and Google (*Vasilaki*). Examples include the £1.2m ActiveAI EPSRC Centre-to-Centre grant (*Mangan*), which establishes a long-term research partnership with leading teams in Australia, and the £2m Brain on Boards programme grant (*Marshall*). *Vasilaki* has secured three grants for her work on neuromorphic engineering, forging links with the Department of Materials Science and Engineering (EPSRC and Leverhulme, £1.8m). *Oliveto* obtained an EPSRC Early Career Fellowship (£1.2m). *Prescott* collaborates internationally via the Human Brain Project (£0.7m).

A particular focus of future research will be the development of explainable AI. *Gilra* and *Vasilaki* recently secured a CHIST-ERA grant addressing causal explanations in reinforcement learning, and *Alvarez* is developing methods for learning cause-effect models from large datasets. *Lu* will focus on interpretable ML for data-scarce domains. We will expand our work on bioinspired robotic vision (*Sun*), supported by additional staff recruitment.

Dependable and secure systems

Research is driven by the challenge of developing systems that are demonstrably dependable and secure. Key problems relate to concurrent systems, for which correctness is tightly coupled to architecture. Hybrid systems, which combine discrete and continuous data, provide particular challenges for smart manufacturing and autonomous systems. Ensuring privacy in modern advanced systems is also an important issue.

The theme is supported by 18 staff (5 professors, 12 lecturers/ senior lecturers, 1 fellow) across the *Algorithms*, *Testing, Verification* and *Security* groups, including four of the most senior UK

academics working in the field (*Derrick*, *Hierons*, *Struth*, *Clark*). Research income was £6.5m, including grants from the EPSRC, EU, Dstl, Google and Facebook.

Highlights include significant contributions to concurrency theory, including completeness/decidability for concurrent Kleene algebras (*Struth,* LIPIcs), decidability/complexity for distributed testing (*Hierons,* IEEE ToC), and notions of correctness and complexity for weak memory (*Derrick*, ACM TOCL). We developed authentication protocols (*Gope,* IEEE TIFS), ciphers (*Kavun,* CRYPTO), and access control methods (*Kaaniche,* IEEE TCC) for resource-constrained architectures and novel techniques in distributed testing (*Hierons,* ACM TOSEM) and verification in the presence of transactional memory (*Derrick*, several EPSRC projects in collaboration with ARM). We addressed compositionality to enable scalability (*Hierons*, EPSRC RoboTest) and the testing of highly concurrent Erlang code (*Derrick*, EU PROWESS). We advanced automation through work on automated reasoning (*Struth,* FAOC), the theoretical basis for model checking (*Ordyniak*, FOCS) and theorem-provers applied to verify the security of real-world applications (*Popescu*, POPL). We use metaheuristics such as genetic algorithms (*e.g., Clark*, Journal Syst. Soft.; *McMinn*, ACM TOSEM) and are one of the few groups to provide theoretical results regarding the effectiveness of these techniques (e.g. *Oliveto*, TCS).

Future plans include exploring the quantitative verification and testing of probabilistic systems, supported by the UKRI Verifiability Node and EPSRC RoboTest project (*Hierons*). We will further develop verification and testing techniques for transactional and non-volatile memory (*Derrick*). EPSRC-funded work on causal inference (*Walkinshaw*, CiTCOM) provides a starting point for addressing large-scale systems. Finally, we will investigate how AI can be exploited for defence and attack (*Clark, Gope* and *Kaaniche*).

1.3 Approach to supporting interdisciplinary research

Through our strategic themes, we carry out research in areas that are interdisciplinary by nature, and seek impact through partnerships with other domains. *Speech and Language* draws on phonetics, linguistics, psychophysics and engineering but also contributes to these disciplines (e.g. computational models of hearing, NLP methods in corpus linguistics). *Healthcare Technology* and *Bioinspired Machine Intelligence* are entirely interdisciplinary themes, in which close collaboration with other research areas (particularly medicine and biological sciences) is key. Approximately 60% of our outputs and 35% of our grants involve collaborations with departments such as Biological Sciences, Neuroscience, Medicine, Psychology, Physics, and Law.

We identify key interdisciplinary areas based on research strength and sustainability and support them through the following mechanisms:

Strategic leadership of interdisciplinary University institutes and centres. We hold leadership positions in: Insigneo (*Clayton*); Sheffield Robotics (*Prescott*); and CATCH (*Christensen*) as well as in three of the four University Flagship Research Institutes - Neuroscience (*Vasilaki, Gilra*), Healthy Lifespan (*Villavicencio*, *Villa-Uriol*), Sustainable Food (*Cunningham*). These facilitate our involvement in large collaborative grants, e.g. the €15m SANO centre for personalised medicine, and lead to interdisciplinary outputs (e.g. Current Biology), and position papers in influential journals (e.g. Nature Food). We nurture future leaders of interdisciplinary research through early engagement with leadership (e.g. *Gilra*, *Villa-Uriol* and *Christensen* held roles in institutes as lecturers), supported by schemes such as Sheffield Leader (Section 2.3).

Appointments in interdisciplinary areas. We recruit researchers with demonstrable ability to work across disciplinary boundaries. Appointments have cemented our links with Neuroscience (*Alvarez*, *Gilra*, *Mangan, Wang*), Neurology (*Christensen*), the NHS (*Lanfranchi*, *Villa-Uriol*),

Cardiology (*Lu*) and Psychology (*Prescott*). Outcomes include interdisciplinary publications in top venues (e.g. Nature Neuroscience) and £3.15m in collaborative grants.

Internal funding to support interdisciplinary research. We invested £800k in interdisciplinary PhD studentships, and co-supervise students with 11 other departments. We organise events that catalyse interdisciplinary collaborations, e.g. an ML workshop for the Faculty of Science. Resulting outcomes include papers co-authored by PhD students in prestigious outlets (e.g. Nature Machine Intelligence) and new collaborations with the Department of Chemistry. We also fund infrastructure for interdisciplinary research (Section 3).

Research software engineering (RSE). We support a rapidly growing RSE group by underwriting 6 posts, an investment of £90k since 2014. The group underpins excellence in research software across the University: in 2019/20, it supported 28 grants, with a total value exceeding £9m. In turn, this leads to interdisciplinary collaborations: *Richmond* (head of RSE) holds interdisciplinary grants totalling £1.4m, including projects on bone disease and tuberculosis vaccine development.

Our future strategy includes investment in these successful mechanisms and capitalising on our strategic involvement in interdisciplinary institutes, which will benefit from the University's recent commitment to invest £13.7m in four flagship research institutes. We have leadership positions in three of these and are forging links with the fourth (Energy) via our new appointment *Gope*.

1.4 Impact strategy, support mechanisms and outcomes

Our impact strategy promotes early engagement with end users of our research across each of our four strategic themes to ensure that impact is embedded from project conception to dissemination. The identification and development of impact opportunities are supported by an impact champion (*Cunningham*), Faculty and University research support services, and the following mechanisms:

Joint appointments. These bridge us with key targets for translating research. *Lanfranchi* has a joint appointment with the NHS, securing more than £400k in health-related grants in the last two years. *Law's* appointment with the Advanced Manufacturing Research Centre (AMRC) led to the involvement of the AMRC in a UKRI TAS Verifiability Node.

Visiting academic appointments. Six industry figures facilitate connections that support research impact. Collaboration with visiting academic *Chakravarthy* (Dstl) led to the foundation of a new University Technology Centre for AI in Defence and Security.

Consultancy. Generous consulting and shared IP arrangements encourage staff to undertake consultancy that can lead to larger impact opportunities. Since REF2014, consultancy income exceeded £1.4m, involving 13 staff and 39 partners. These partners include SMEs such as Elephant Gin (*Law*) and Alchemy Machines (*Aletras*) and large companies such as Samsung (*Ragni*). The *Large-Scale Data* impact case study arose from consultancy contracts with Public Health England (to develop the "Active 10" app) and JustGiving.

We proactively identify impactful research and support it via reduced workloads and impact sabbaticals. Professional knowledge exchange colleagues assist industry engagement, both in the Faculty (2 FTE) and in a central impact and knowledge exchange team (13.2 FTE). From the latter, we received Impact Accelerator Account, HEIF and Commercialisation of IP funds of £311k in the assessment period. Our RSE group is deployed to accelerate impact, supporting, e.g. our case study *Combatting Disinformation* by rapid delivery of an online COVID-19 disinformation dashboard.
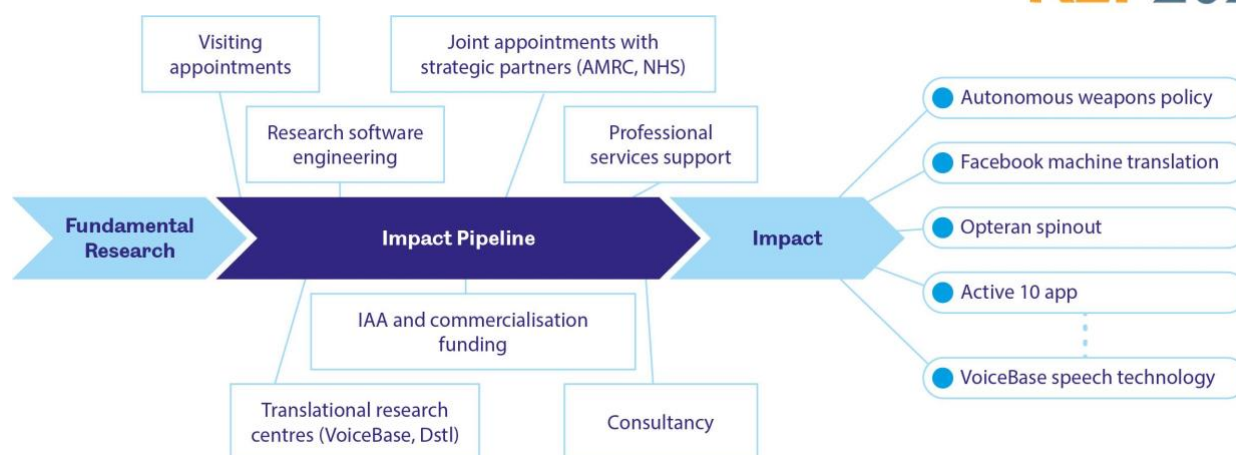
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Figure 2: Impact pipeline

Our successful impact strategy is apparent from the quality and diversity of our selected case studies, which range from influential research informing policymakers (*Banning LAWS*, *Combating Disinformation*) to speech and language research that underpins the technology of VoiceBase, Facebook and Microsoft (*Automatic Voice Recognition*, *Machine Translation*), and research on analysing data at massive scales, which has impacted hundreds of thousands of people (*Large-Scale Data*). Our successful impact pipeline is evidenced by many projects at various stages of translation, e.g. working with South London and Maudsley NHS Foundation Trust, we used the open-source GATE text engineering technology developed in our *speech and language* theme to find a link between symptoms of schizophrenia described in a patient's clinical records and the likelihood of that patient being admitted to a hospital. In our *bioinspired machine intelligence* theme, fundamental research on the visual system of the honeybee has been translated via Opteran (*Marshall*). The company is pioneering bioinspired silicon-based solutions for computer vision and autonomous decision making and has raised £2.1m in seed funding.

Existing case studies and new projects in our impact pipeline will provide the starting point for developing our future impact agenda. Our centres funded by VoiceBase and Dstl will be crucibles for translational research, further feeding our impact pipeline. Our impactful work on misinformation will be supported by additional academic appointments.

1.5 Open research and research integrity

Research integrity is a fundamental component of research excellence. We uphold principles of honesty, responsibility, fairness and accountability, supported by commitment from the institution, our staff and postgraduate research (PGR) students. Our strategy for developing open research and research integrity is based around the following three pillars:

Developing a culture of research integrity. We adopt an approach to research that is underpinned by honesty and transparency and supported by rigorous methods and reporting principles. Training is a key factor in achieving this. All PGR students and new staff complete a course on *Professional Behaviour and Ethical Conduct*. We run an annual seminar on peer review, targeted at PGR students and postdoctoral research assistants (PDRAs). All staff and PGR students complete online training in unconscious bias and protecting research data. We ensure that informed, auditable oversight of research integrity occurs in practice. Ethics, data governance and research methodology are considered at all PGR progression/review points and in probationary staff reviews. We maintain a panel of trained ethics reviewers, supported by a bespoke online ethics approval system. Audits of our ethical approvals are undertaken by the University Research Ethics Committee. Declarations of interest are systematically reviewed and

updated annually. Faculty approval is required for the appointment of PGR examiners, with due regard to appropriate competence and independence. Finally, we seek to establish a culture in which concerns about research integrity can be raised without fear of reprisal. A procedure for whistleblowing is outlined (see REF5a); however, we emphasise that honesty is paramount.

Support for open access (OA). We ensure that publicly funded research is accessible to the public, industry, and the wider academic community, and we adhere to University-wide principles of OA. To ensure maximum discoverability of our research, we aim to put all outputs in White Rose Research Online, our shared repository with Leeds and York (green route). The 1,463 outputs deposited over the assessment period were downloaded over 99,000 times. This is our preferred route, ensuring equity in publishing opportunities regardless of available funding; we also publish outputs in fully OA journals, supported by a Departmental fund, or hybrid where required for funder compliance. In addition, staff increasingly submit papers to preprint services such as arXiv to ensure timely dissemination of research findings. Twenty staff have editorial roles in journals that support open research.

Support for open data, open methods and open-source software. This support is the core of reproducibility, being intimately linked to the culture of research integrity we seek. We publish software and datasets to the community through our institutional data repository, ORDA. The *speech and language* theme has been particularly active in sharing open data, including the Lombard Grid, an audiovisual speech corpus, and CHiME, a series of ASR challenges. Our RSE group supports a doctoral training module on software methodologies and tools, underpinning our commitment to the reproducibility of results. We promote open training to the community, e.g. the annual Gaussian Process Summer School (*Lawrence*, *Alvarez, Smith*) is a beacon of the open approach to research training. The related GPy open-source framework for Gaussian Processes is distributed through GitHub, with 431 users and 64 contributors.

Going forward, our strategy is to recognise and promote methodological excellence within our research, e.g. by leveraging our capacity in RSE to support and educate staff and PGR students in open research software. We will develop short courses in open data and software for research locally and then make them available to the whole University as a beacon activity; *Derrick's* experience as chair of the University OA Advisory Group will facilitate this. We will also promote awareness of the ethical requirements and practices of other disciplines. *Lanfranchi* is our ethics lead and has a joint position with the NHS; she is well positioned to advise on research integrity within the *healthcare technologies* theme, which increasingly involves clinical collaboration.

1.6 Strategic priorities for the next five years

Our ongoing strategy is to capitalise on our excellence and to grow our investment around our four key themes. Priorities in the next five years are as follows:

Further develop collaborations in our strategic themes. Collaborations allow us to better understand challenges and act as vehicles for a broad range of impact. These collaborations will be facilitated by further growing our academic staff to 73 to enable theme, institute and end-user collaborations while maintaining a balanced growth across the four themes. Our first priority is to increase our capacity in machine vision, which will provide new opportunities for interaction with Insigneo, CATCH and Sheffield Robotics. Collaborations benefit from Sheffield's commitment to invest £13.7m in four flagship research institutes, all of which we are linked to. Finally, we will enhance collaborations with the AMRC and High Value Manufacturing Catapult through our *dependable and secure systems* theme.

Exploit and contribute to wider infrastructure and services. Significant opportunities for leveraging infrastructure in areas of Sheffield's strengths are the £43m Industry 4.0 investment in the AMRC and the HPC provision at the Faculty, University and national levels. IT infrastructure will benefit from a £10m University investment. A key aim will be to grow our HPC infrastructure at the scale necessary to support our research in ML. To address this, we will seek collaborations with other academic institutions and commercial cloud computing providers.

Revitalise and exploit our physical infrastructure. We plan to be in extended and refurbished accommodation by the end of 2022, enabled by University investment of £10.5m. We will use this opportunity to re-equip our groups, stimulate cross-group research and enhance the PGR student environment. Our refurbished building will offer an improved environment for knowledge exchange and external engagement, facilitating our future impact strategy, which stresses early and close engagement with business, the public and the third sector.

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2. People

2.1 Overview

Our REF2014 plans have led to significant, strategic growth within our key themes. The Department now has 55 academic staff, 2 academic fellows, 72 researchers; among those 2 academic fellows, 6 University teachers, 39 professional support staff, and 86 PGR students of which 53 are Graduate Teaching Assistants (GTAs). Each theme is supported by a mixture of senior research leaders, mid-career staff and early-career researchers (ECRs) with an excellent trajectory.

We take great pride in fostering a friendly, collegial and nurturing research environment. Our approach to staffing and recruitment is informed by deeply held EDI values, recognised through a Silver Athena SWAN award. The University is in the top 100 of the Sunday Times Best Employers List, is a Top 5% Stonewall employer and maintains an HR Excellence in Research Award and Disability Confident accreditation.

2.2 Staffing and recruitment strategy

Our staffing and recruitment strategy ensures that we have the breadth and depth of research excellence needed to address our research themes. Challenges have been to appoint outstanding individuals in competitive areas (e.g. cybersecurity, ML) and to attract senior academics to establish new groups and strengthen the leadership of existing groups.

Figure 3: People, staffing and recruitment strategy

We achieve these aims in two ways. Firstly, we develop a distinctive five-year support package for ECRs, in the form of internally-funded proleptic fellowships. These offer guaranteed progression to an open-ended academic position, subject to meeting standard probation requirements. Secondly, we support new lecturers and professors with an attractive package including internally-funded PGR studentships and a reduced teaching load for 2-3 years.

This strategy has been successful in attracting outstanding talent. Over the assessment period, we appointed 2 fellows (1 female), 17 lecturers (5 female), 7 senior lecturers (1 female) and four professors (1 female). These contribute to the excellence of our research themes as follows:

Speech and language. Research in multilinguality and cognitively motivated NLP was supported by the appointment of *Villavicencio* to a personal chair. Three senior lecturers (*Goetze*, *Barrault*, *Lin*) bring expertise in deep learning methods. Lectureship appointments *Ragni* and *Aletras* have progressed rapidly, the latter winning £508k in grant income since appointment. We deployed an internally-funded fellowship to recruit *Scarton* in the competitive area of machine translation. She has already won a major grant (EPSRC £446k).

Healthcare technologies. We recruited *Lanfranchi* to a joint position with the NHS: she has secured £547k in grants since appointment, many with clinical partners. *Villa-Uriol* and *Yang* bring physiological modelling and machine learning expertise, cementing our links with Insigneo. *Wang* is a joint appointment with Neuroscience and SITraN, bringing expertise in bioinformatics. *Christensen* has developed extensive clinical collaborations through work on the assessment of neurodegenerative disorders (Journal of Neurology) and secured an EU Marie Skłodowska-Curie Training Network (TAPAS).

Bioinspired machine intelligence. *Prescott* was recruited to a chair to grow links with Sheffield Robotics, where he is the Director. Lecturers *Mangan* and *Sun* bring expertise in bioinspired robotics and machine vision. Research in core ML methods was strengthened through *Alvarez* and *Lu*, who have earned £839k between them in grants, with both securing an EPSRC New Investigator Award. Expertise in graph clustering was strengthened by *Peng*, who publishes in the competitive SODA conference. *Gilra*'s work on recurrent spiking neural networks (eLife) cements our links with the flagship Neuroscience Institute. A proleptic fellowship was used to attract *Smith*, whose work on ML methods for pollution modelling is likely to become a future impact case study.

Dependable and secure systems. *Clark* was recruited to lead our new *Security* group, supported by strategic University investment of £1.2m. The group now comprises 5 academics, 3 PDRAs and 10 PGR students. Appointments in the *Security* group bring expertise in cryptographic algorithms (*Kavun*, *Kaaniche*), information flow security (*Popescu*) and internet-of-things (IoT) security (*Gope*). Our expertise in model checking was bolstered by *Ordyniak*, who publishes in top venues (e.g. Algorithmica). Leadership in testing was supported through the chair appointment of *Hierons*;

with new senior lecturer *Walkinshaw* he has won an EPSRC grant on causal inference for testing computational models. Capacity in verification was increased by *Beohar* and *Dimitrova*, the latter having expertise in hybrid systems and potential links with the AMRC.

All Category A staff are on open-ended contracts. We offer open-ended contracts to researchers on fixed-term projects wherever appropriate, taking account of longer-term strategy and plans. Currently 35% of researchers are on open-ended contracts (up from 24% in the last period).

Going forward, a plan has been developed with Faculty approval to grow our academic staff to 73 within 6 years. We will recruit a chair and two further lecturers in machine vision, supporting our *bioinspired machine intelligence* and *healthcare technologies* themes. The *dependable and secure systems* theme will be strengthened by a chair and two lectureships in distributed systems and an additional lectureship in security. An internally-funded fellowship will support the pipeline of researchers working on social media analysis in the *speech and language* theme.

2.3 Staff development and support

Our strategy is to provide support that enables high performance, agility, leadership, and intellectual and professional development. During the assessment period, a particular focus has been to support the progression of fellows to academic positions and to ensure that new appointees and ECRs become well-embedded in the unit and rapidly progress.

The University's Academic Career Pathways (ACP) framework provides a structure for academic staff progression from early career to professorship. Research and impact are explicitly recognised within the ACP framework, with appropriate expectations set to enable achievement to be rewarded in terms of progression. All staff have an annual review meeting that focuses on career planning and identifies ongoing training needs. Strong staff engagement with this process exists in the Department (e.g. 97% of staff completed a review in 2019).

Supporting fellowships. Faculty professional services provide support by arranging mock interview panels, and workloads are adjusted for those developing fellowship applications. In the assessment period, seven of our staff held fellowships, three of which were ECRs (see below). *Bontcheva* won an EPSRC Career Acceleration Fellowship while working part-time, and *Specia* was awarded an ERC starting grant. In both cases, the fellowships supported work that led to an impact case study. *Marshall* was awarded an ERC Consolidator grant and *Clark* held a Royal Society Wolfson Research Merit Award.

Supporting the development of ECRs and PDRAs. We proactively mentor our ECRs to ensure their retention and career progression, with close involvement of the Head of Department (HoD). The success of this approach is exemplified by *Oliveto* and *Richmond*, who were initially supported by Sheffield Vice-Chancellor Fellowships. Both were subsequently appointed to senior lecturer and won EPSRC Early Career and RSE Fellowships respectively. *Croucher* won a second RSE Fellowship and progressed to Head of Research Computing at the University of Leeds. An extensive range of development modules is available to PDRAs, including courses on entrepreneurship, research management, academic writing and media training. A professor and EPSRC panel chair (*Clark*) runs a proposal-writing training module for ECRs and PDRAs.

Implementing the Concordat to support the career development of researchers. We have mapped our activities against the Concordat and implement its principles through an induction programme, annual reviews and away days for researchers. The latter covers topics such as industry engagement, frequently with an invited speaker. The "Think Ahead" development

programme, coordinated by a dedicated member of the University's professional services team, further promotes employment and professional development opportunities.

Supporting probationary staff. Probationary staff have a reduced teaching load for three years (set as 50%, 70%, and 90% of normal load). New appointees have a mentor and devise a probation plan with the HoD. They meet monthly with the HoD/Deputy HoD during the probation period. This close mentoring approach is successful: all 10 staff who completed probation exceeded their grant income target of £130k, with a mean grant income of £344k. Half of these staff completed probation a year early.

Developing future leaders. Research groups are typically led by a professor. In some cases group heads are new senior appointments (*Clark*, *Hierons*), but in most cases future leaders are developed from existing staff (e.g. *Bontcheva*, *Hain*), with a succession pipeline supported by departmental mentors or institutional programmes such as *Sheffield Leader*. Twenty-six staff participated in these programmes (11 female, 15 male) and have gone on to assume major leadership roles within the Department (e.g. group heads, HoD, Director of Research) and in the wider University (*Christensen* is Faculty Director of EDI; *Derrick* is Vice President for the Faculty of Science).

2.4 Support and reward for research and impact

Research and impact are rewarded through the ACP framework, which sets out transparent expectations to achieve career progression. In the assessment period 23 staff were promoted, including 6 to personal chairs (3 women), which reflects the high quality of our staff, our robust processes for supporting career progression, and our readiness to recognise and reward achievement in research as well as broader contributions in leadership, professional standing and wider engagement.

Sabbaticals allow one semester of leave after seven and are allocated according to a rolling schedule, looking several years ahead. Part-time staff take study leave on a pro-rata basis. Notable outcomes of 15 sabbaticals in the assessment period include the following: *McMinn* developed a new relationship with Facebook, leading to a £41k grant on search-based testing; *Sudholt* published four journal papers (Artificial Intelligence, Algorithmica, IEEE TEC) and four conference papers (GECCO); *Prescott* visited the Sage Centre for the Study of the Mind at the University of California Santa Barbara as Distinguished Fellow, leading to a co-authored article (Trends in Neuroscience); and *Hain* visited the Nagoya Institute of Technology as Visiting Professor, leading to a student exchange and collaboration on a grant proposal. We also fund shorter research visits that are likely to lead to high-quality outputs, e.g. *Struth*'s visit to Macquarie University and Data61 in Sydney led to two collaborative papers on quantitative information flow.

We keep teaching and administrative loads in balance through a workload allocation model so that time for research and impact is protected. We also support research through spending on teaching-specialist staff; since 2014, we have appointed 6 university teachers (two were funded through a £1m Institute of Coding grant) and increased spending on GTAs from £31k in 2014/15 to £90k in 2019/20.

2.5 Support for postgraduate research students

Our strategy is to create a diverse community of PGR students with a broad range of specialist skills and intellectual perspectives. We aim to attract the brightest PGR students from the UK and internationally, driving recruitment with internally-funded scholarships (£3m over the assessment period) and through our CDT, which will sponsor 60 PGRs over 2019-2027. We attract diverse

candidates by advertising widely and support self-funded applicants where possible (e.g. via partial fee scholarships). Our success is evidenced by a diverse cohort (13% EU and 59% international representing 38 countries) and PGRs with first-authored papers in top journals (e.g. *Paetzold*, Journal of AI Research; *Mirheidari*, Computer Speech & Language; *Osuna*, IEEE Transactions on Evolutionary Computation).

Supporting progression

All PGRs are assigned a primary supervisor, an independent advisor from the same research group and a panel chair from a different group. We supplement University-required annual reviews with six monthly panel meetings, enabling clear and timely oversight of progress. For students registering in 2015/16, 89% submitted within their four-year time limit. A 2019 Postgraduate Research Experience survey showed high overall satisfaction (82%), with positive responses for supervision (86%), skills development (89%) and resources (85%).

Skills training and preparation for future careers

All PGR students complete training courses in research integrity, teamwork and presentation skills and must formulate a data management plan. Each student has a dedicated workspace and desktop computer and an allowance of £1,500 for conference participation. Outcomes include numerous prizes for presentations at international conferences (e.g. *Ge*, International Symposium on Search-Based Software Engineering 2017; *Naith*, International Conference on Crowd Science and Engineering 2018).

We build connections with potential employers through industry talks, engagement with visiting professors (e.g. *Leidner,* Thomson-Reuters), collaboration with our CDT sponsors (e.g. Amazon, NHS Digital) and internships (e.g. Apple, Microsoft, Baidu, Google, Electronic Arts). Success is evidenced by the breadth of professional careers that our PGRs pursue after graduation, including postdoctoral positions (e.g. *Loweimi*, Edinburgh; *Armstrong*, Cambridge; *Rabehaja*, Macquarie) and fellowships (*Richmond,* EPSRC RSE Fellowship). Several have progressed to lectureships, e.g. *Usman* (UET Lahore), *Roberts* (KCL), *Alharbi* (King Saud University). *Derczynski* and *Augenstein* hold professorships at the University of Copenhagen, with *Augenstein* leading the NLP group (line managing 44 people). Our PGRs have taken up significant roles in tech startups (e.g. *Mokharam*, EmoTech) and have been employed by industry leaders (e.g. *Gomes*, Amazon; *Doulaty*, Facebook).

2.6 Equality, diversity, and inclusion

Our strategy is to ensure that our practices in recruitment, staff support and career development fully harness a diverse pool of talent, enabling us to advance our research themes. We implement this strategy by embedding EDI throughout departmental processes. All staff undertake unconscious bias training; a gender balance is ensured in all committees and appointment panels; and search committees seek applicants from underrepresented groups. The University has an active Disability Staff Network. Positive responses in the 2018 University Staff Survey confirm that the Department recognises and values diversity and difference (97%). Over the assessment period, we appointed eight women to academic (lecturing or fellowship) positions.

Addressing gender equality. Our active engagement with Athena SWAN has led to both Bronze (2013) and a Silver (2016) awards. Through our action plan, mentoring by the HoD and the University's peer mentoring scheme, we have been successful in improving gender equality in our pipeline from ECR to professor. We had 23 promotions, of which 6 were female. We increased the number of female professors from zero in 2014 to four over the assessment period, three of whom

were promoted from within the Department. Currently women account for 36% of lecturers, 22% of senior lecturers/readers/advanced fellows and 17% of professors. Female academics have obtained £8.6m in external funding since 2014, generating 27% of our research income. This statistic is impressive, given that three women were recent appointments (<1y) and that, prior to 2016, none were professors. Female senior leaders include our Director of Research, two research group heads, the Faculty Director of EDI and other leaders in the wider University.

Eliminating discrimination and promoting diversity. We are a proudly multicultural department with 32 international academic staff of which 22 were appointed during the assessment period. Firmly embedding EDI principles in our recruitment processes has led to an increased proportion of BAME staff; with 25% of staff self-reporting as BAME. We are committed to supporting our LGBTQ+ staff and PGRs, as evidenced by the University's Stonewall Top 100 Employers position for seven years running. We actively support different lifestyles, for example we have flexible arrangements for a number of academics with partners in different cities. In our most recent staff survey, 96% of staff agreed that they could talk openly with their line manager about flexible working. We offer targeted help to staff and PGRs with protected characteristics (e.g. changes in working pattern to accommodate disabilities). Support for international staff includes flexibility with overseas working, which was particularly important during the COVID-19 pandemic.

Supporting mental health and neurodiversity. The Faculty has a wellbeing officer who provides expert one-to-one support and signposting to students, including PGRs. We plan to further buttress this support with a dedicated wellbeing officer for the Department. We are liaising with IBM on their industry-leading work in neurodiversity to gain greater insight into practices for recruiting and supporting neurodiverse staff; this has informed our ongoing Athena SWAN action plan.

Parental leave and childcare. In addition to statutory maternity, adoption and shared parental leave, staff on leave can elect to perform up to 10 days of paid work without loss of statutory pay ('keeping-in-touch' days). Since 2014, 12 staff members have taken parental leave. All staff taking parental leave remained in employment with the Department after 18 months. One staff member received an award of £10k through the University's Women Academic Returners' Programme (WARP), which provides financial support for women to mitigate the impact of extended leave on research.

Equality and diversity issues in the preparation of this REF submission. In accordance with the University Code of Practice, four principles were applied throughout all stages of our submission: *transparency*, *consistency*, *accountability* and *inclusivity*. Staff with a leading role in our REF submission (3 males, one female) have undertaken unconscious bias training; output selection was overseen by a female academic. The selection of outputs was guided by anonymous internal and external reviewers. Subsequent validation showed that we had not introduced significant gender bias in the selection of outputs. 40% of our impact case studies are led by women (20% of academic staff are women).

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3. Income, infrastructure and facilities

3.1 Overview

We ensure that our four research themes are well supported through income capture, infrastructure provision and access to facilities. A particular focus has been to diversify our support base by increasing our UKRI and industry funding. This diversification reflects opportunities: the

synergy between UKRI funding priorities (Industrial Strategy, Made Smarter), industry demand for our research (in areas such as SLT), and growth in our research strengths and ambitions. Diversification was also a response to the challenge of uncertainty regarding UK participation in EU research schemes. The key outcomes are an increase in grant income from £18.8m in the last period to £32.5m and more than doubling industry income from £875k to £2.1m.

Our underlying strategy has been multi-pronged. We have actively recruited in areas of strategic importance, making professorial appointments to enhance leadership and appointments to fill gaps in our expertise (see Section 2.2). This has ensured sustainability of funding across our research themes. We have sought and achieved positions of leadership in major grants (e.g. EPSRC programme grants, fellowships, coordination of EU grants). Time for research and impact is protected through investment in teaching-specialist posts, sabbaticals and funded short-term study leave (see Section 2.4).

Appointing staff with interdisciplinary profiles has created opportunities for new funding streams (e.g. Rosetrees Trust). Our interdisciplinary collaborations allow us to leverage a wide range of facilities across the University. We leverage and contribute to HPC provision across the University and through national initiatives such as JADE. This reflects the increasing importance of HPC to the ML interests of almost all of our research groups.

3.2 Income

Research grant capture. Our research income increased from £18.8m (REF2014) to £32.5m, with UK, EU, and industry funding in each of our four strategic themes. We have been highly successful in obtaining EU funding; this reflects the international and multidisciplinary nature of our work and the close alignment of our strengths with EU and UK priorities. We grew our EU funding from less than £10m (REF2014) to £15.4m. We collaborated with leading European scientists on 39 EU-funded projects, involving 177 universities, 92 companies and 85 charities, and coordinated 5 FP7/Horizon 2020 grants (PROWESS, WeSenseIT, Pheme, CONTESSA, SETA). We achieved diversification of our grant capture: 56% of our funding was from non-EU sources, an increase from 49%. UKRI funding increased from £6.5m to £12.4m. Income from charities was £717k, including grants from the British Heart Foundation, Wellcome Trust, Rosetrees Trust and Alzheimer's Society. 62% of our submitted papers came from funded projects, as did four of our impact case studies. New staff have been responsible for £6.8m in external funding and approximately 50% of our outputs.

Large grant leadership. Leadership in all four of our themes is demonstrated by major single grant awards, reflecting the excellence of senior research leaders within the groups. In the *bioinspired machine intelligence* theme *Marshall* leads a collaborative EPSRC programme grant, Brains on Board: (£4.8m, £2.2m to Sheffield). This was supported by a lecturer appointment (*Mangan*). Outputs from the grant include interdisciplinary papers in top journals (e.g. Proceedings of the Royal Society Series B) and a spin-out company (Opteran). In the *dependable and secure systems* theme, *Clark* leads the £4.9m Research England IoT innovation project PITCH-IN, a collaboration with Oxford, Cambridge, and Newcastle. In the *speech and language* theme, *Hain* held the EPSRC Natural Speech Technology programme grant, which laid the foundation for our CDT and VoiceBase centre.

Fellowships. Fellowship income totalled £5.1m. An ERC Starting Grant to *Specia* (£1.2m) led to an impact case study on machine translation, which underpins technology used by Facebook and Microsoft. A £1.2m ERC Consolidator Grant to *Marshall* funded his research on bioinspired robotics, leading to a programme grant (see above) and first-authored interdisciplinary publications

in competitive outlets, e.g. eLife. *Richmond* and *Croucher* won 2 of the 7 awards in the first round of the EPSRC Research Software Engineering Fellowships. *Richmond* has since established a team of 12 people (see Section 3.3); *Croucher* progressed to Head of Research Computing at the University of Leeds. *Oliveto* won an EPSRC Early Career Fellowship for his work on the rigorous runtime analysis of bioinspired computing (£1.3m). Over the assessment period, he published over 50 papers in, e.g. Theoretical Computer Science and IEEE Transactions on Evolutionary Computation.

New appointees. We support new appointees with dedicated grant writing workshops. EPSRC First Grant/New Investigator Awards were obtained by *Vlachos* (non-monotonic incremental language processing), *Alvarez* (one-shot learning of human motion), *Lu* (sparse features for fMRI analysis) and *Ordyniak* (parameterized algorithms).

Industry income. This increased from £875k (REF2014) to £2.1m. Notable achievements include two new industry-funded centres, with funding totalling £1.4m. The Silicon Valley company VoiceBase funds a centre employing 12 people to support *Hain's* research in ASR. A Dstl-funded University Technology Centre for AI in Defence and Security was established in 2020. Staff have been successful in obtaining research funding from tech companies, a total of £510k in the assessment period from Amazon, Google, and Microsoft, e.g. a Google award to *Barker* supported his work on the influential series of CHiME ASR challenges.

PGR income. Our reputation for research excellence makes us an attractive environment for PGR students; since 2014 our PGR base has expanded by 25%. We have strategically invested our own funds in PGR scholarships to support new staff and major grants; since 2014 we spent ~£3m and have committed £3.35m over the next 5 years. We were awarded a UKRI CDT in Speech and Language Technologies, which will train 60 PGRs over 2019-2027. This award provided leverage for investment in staff within our *speech and language* theme, with the subsequent appointment of *Barrault*, *Goetze*, *Lin*, *Ragni*, *Scarton* and *Villavicencio*. The CDT has significantly grown our industry connections, leading to collaborative funding from Amazon Research, Google, Microsoft Research, NHS Digital and others. We participate in the EU Marie Skłodowska-Curie ITN TAPAS (*Christensen*, *Barker*, £454k) and NeuTouch (*Prescott*, £248k).

By diversifying our support base and building connections across disciplines and with external partners, we are well positioned to respond quickly and flexibly to changing priorities and opportunities. A recent illustration is *Lu's* success in winning a highly competitive US National Institutes for Health AI in Health and Care Award in 2020 (< 8% success rate, £504k) that brought together our ML expertise with clinical expertise from Sheffield Teaching Hospitals NHS Trust.

3.3 Infrastructure and facilities

Our growth in staff numbers is matched by investment in infrastructure and facilities, ensuring that our themes are well supported to generate excellent research and significant impact. Key investments during the assessment period are highlighted below.

High-performance computing. Our strategy is both to fully exploit the extensive HPC facilities provided by the University and to further contribute to them. We maintain a server room for specialist equipment but increasingly we are investing in additional nodes for the central HPC clusters Bessemer, ShARC and Iceberg. Together, these provide 350 worker nodes, 6500 CPU cores, 49 TB of RAM, 60 GPUs and 1425 TB of fast network storage. 313 members of our staff and PGR students have accounts for these HPC facilities. We supplemented University investment in HPC facilities with £480k of equipment, in addition to £800k spent on large-memory nodes and GPUs for ML. Recognising the increasing importance of deep learning, particularly for our *speech*

and language and *bioinspired machine intelligence* themes, we provide a significant number of state-of-the-art GPUs to individuals (eight in 2019) and our CDT (three 6GB NVIDIA Titan cards). We were the first UK university to purchase an NVIDIA DGX-1, an accelerated platform for deep learning. We are part of a consortium that has access to the JADE Tier 2 GPU cluster, designed for the needs of machine learning and related data science applications; this also supports work on machine translation. Going forward, a University £10m plan to deliver a new Research IT and Innovation Strategy has been agreed upon.

Sheffield Robotics. Our close collaboration with Sheffield Robotics and links to the AMRC provides access to a wide range of specialised equipment and facilities. In addition to the 200m^2 Sheffield Robotics lab, a human-robot interaction lab (17m^2), a motion capture lab (60m^2), two hangars (400m^2) and a workshop (40m^2) are available. Equipment includes Kilobots (*Marshall* on the DIODE project); KUKA iiwa (*Law* and *Gaizauskas*, EPSRC Network Plus Connected Everything project); Jaguar 4x4 rovers, Griffon dynamics Octocopters, and DJI Phantom 4 (*Law*, EPSRC UK-RAS Field Robotics Challenge 2016); iCub (*Prescott*, Horizon 2020 WYSIWYD and Cyberselves projects); 3D printers (*Marshall*, Green Brain and Brains on Board projects) and dedicated technical support (2 FTE). Sheffield Robotics has won over £1.5m in EPSRC capital awards since 2014, and we supported it with an additional £0.9m for staff and equipment.

Research software engineering. Our RSE group, one of the largest in the UK, grew from 2 FTE in 2016 to 11 FTE. The group largely sustains itself on grant income, but together with central IT services we underwrite posts to offer staff job security and so to ensure retention. They have been instrumental in producing software usable by stakeholders, e.g. a web service for fact-checking used by journalists was developed (Rumour Analysis Service (RAS) project, funded by the Google Digital News Initiative and WeVerify, *Bontcheva*), and they are critical to our reproducibility strategy (see Section 1.5). The team contributes widely to the national RSE agenda through guidance for reproducible research (via The Turing Way with ATI), national training for HPC (via Software Sustainability Institute fellowships and HPC carpentry), and leadership (via a Future RSE Leaders workshop and an RSE Leaders panel) and includes two of the twelve members of the Board of Trustees of the Society of Research Software Engineering.

Facilities for specific research clusters. We have an apiary and a beekeeper to support the Brains on Board project and invested £50k to start the *Security* group (specialist forensics equipment, oscilloscopes, and experimental robotics). Involvement in University interdisciplinary research centres and flagship institutes gives access to specialised equipment, such as the CATCH "home lab", an instrumented living space for supporting research on disabilities, e.g. dementia (*Christensen*). *Lanfranchi's* joint appointment with the NHS has resulted in access to clinical facilities, feeding into over £600k of grant funding. *Wang's* work is supported by secure computing facilities provided by Genomics England, leading to two grants (over £900k). SANO (see Section 1.3) provides HPC infrastructure to support computational medicine research.

Technical and research support staff. Our technicians (12 FTE) support software and hardware technologies, including a dedicated server room. Since 2014, the expansion of our robotics activities within the *bioinspired machine intelligence* theme necessitated the appointment of a dedicated safety officer. The Faculty has established a pipeline of technical staff through the Engineering Apprenticeship Scheme, in which apprentices rotate around departments before settling into an open-ended position. The result is technical staff with well-rounded expertise, able to provide software and hardware support. We invested £29k in the training of technical support staff. Our research support team (8 FTE) assists the development of funding bids and grant management and identifies potential industrial collaborators. A further 6 FTE provide professional support to specific projects and the CDT.

The Diamond. Completed in 2015 at a cost of £81m (19,500m^2), the Diamond is the largest capital investment ever made by the University. Within this, the MindSphere Lounge provides a collaboration and IoT demonstration space for the University, Siemens and local business (*Clark* is the academic lead). The iForge maker space provides 3D printing, CNC and laser cutting and is available to all staff and PGRs (e.g. for the construction of bespoke hardware).

Research laboratories. Our main office space and research laboratories are in the Regent Court building. We strategically maintain offices in multidisciplinary spaces, which encourages collaboration and provides additional space for equipment (e.g., Sheffield Robotics). A key part of our ongoing infrastructure strategy is to refurbish Regent Court (an estimated cost of £10.5m plus £1.5m for a student innovation hub). The overall space will increase by 35% and meeting space will increase by over 50%. The refurbishment will enhance our facilities for collaborative research (e.g. informal working spaces, a large social area, breakout rooms) and opportunities for engagement with the end users of our research (e.g. demonstration spaces).

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

4.1 Overview

Our strategy to facilitate collaborations and widespread impact depends on the creation of an environment for excellent research: we ensure that our researchers have the necessary time and support to develop significant collaborations at the international, national and regional levels. The previous sections outlined our pipeline for translating fundamental research into real-world impact (Section 1.4) and described our staffing strategy (Section 2) and underpinning infrastructure investment (Section 3.3). Here, we highlight the major outcomes arising from our strategy and actions.

4.2 Research collaboration

Much of our most impactful work arises from sustained, often interdisciplinary, collaborations. 84% of research outputs produced during the assessment period involved collaborators from a different discipline or university. 83 research grants involved an industrial partner or another university.

International collaboration. International best-with-best collaborative projects facilitate world-leading research. We collaborated on 44 EU projects and coordinated 5 EU FP7/Horizon 2020 grants totalling over £3.3M. We also collaborate with a range of international companies and have received nearly £2M in funding from them. Examples include VoiceBase, BioGen, Amazon and Microsoft. Collaborations are also sustained through our involvement in international centres. ActiveAI brings together world leaders in entomology, neuroscience, biorobotic modelling and computational neuroscience to develop new algorithms for robust and efficient learning for autonomous robotics. SANO (see Section 1.3) is funded by the EU and Polish government and *Clayton* is on the Scientific Committee.

We also support individual collaborations: our internationally leading research has attracted 99 visitors from 26 countries. Visits of our staff to international collaborators include world-class institutions such as the University of Pittsburgh, Indian Institute of Science Bangalore, ETH Zürich, University of Zürich, KTH Royal Institute of Technology Stockholm, and Yale University.

Approximately 60% of our submitted outputs had an international co-author, with 40% externally funded and 20% stemming from individual collaborations.

National and regional collaboration. Since 2014, our staff held grants of £15.2m with 40 UK academic collaborators. Of our papers, 12% have been co-authored with other UK universities. Programme grants have been effective at establishing long-term collaborations with national academic partners, e.g. Natural Speech Technology (*Hain*, EPSRC £6.2m) supported a collaboration with Edinburgh and Cambridge, leading to significant growth in our *speech and language* theme and ultimately to our CDT.

Within the Sheffield Region our work with Sheffield Teaching Hospitals NHS Trust led to further NHS collaborations (Sheffield Children's Hospital, Rotherham General Hospital). Outcomes include technologies for remote healthcare monitoring and the early detection of conditions, e.g. diabetic retinopathy, funded by 7 projects totalling £331k (*Lanfranchi*, *Villa-Uriol*). We collaborate with Sheffield mobility-tracking company The Floow, funded by the EU SETA project (*Ciravegna*, £1.03m), and HumanStudio on virtual/augmented reality for digital heritage (*Maddock*, funded by the AHRC and leading to a Festival of the Mind exhibit; see below).

4.3 Engagement with key research users, beneficiaries, and audiences

Our strategy is to identify key research users aligned with our four research themes and engage with them through collaborative research projects, technology centres, joint appointments, spin-out companies, our CDT and our industrial advisory board (IAB). Key users include IT companies and the industrial sector, the NHS, education, and policymakers. Our impact pipeline (Section 1.4) plays a crucial role in sustaining long-term, productive engagements with key research users.

Within the *speech and language* theme, engagement has been driven by strong commercial demand for our SLT research. Our ASR technology adds $120m to the value of VoiceBase (*Automatic Voice Recognition* impact case study). Automatic translations in Facebook are underpinned by our research on quality assessment for machine translation (*Machine Translation* case study). ZOO Digital joined our IAB and is now co-developing technology for dubbing video content through an Innovate UK grant (MAUDIE, £314k). Initially attracted by the CDT, Huawei are now supporting SLT research with a further £700k in funding.

The *healthcare technologies* theme engages with key research users (NHS, Public Health England) through research projects, some of which have been catalysed through a joint appointment with Sheffield Teaching Hospitals (*Lanfranchi*). *Ciravegna's* work on mobility tracking led to an impact case study and a spin-out company, Aeqora Ltd. *Brown's* work with SME Passion for Life Healthcare (PFLH) demonstrates how engagement with research users enriches our research. A discussion with PFLH suggested that methods developed in our Department could be applied to the acoustic monitoring and diagnosis of sleep disorders, which led to our first Knowledge Transfer Partnership award and a growing research stream on the health applications of acoustic monitoring, supported by a PFLH-funded PGR studentship and a subsequent Innovate UK grant (BRAHMS, £243k).

In the *bioinspired machine intelligence* theme, a key beneficiary of *Prescott's* research is the education sector: his work on bioinspired robot control is embedded in the MiRo robot, marketed through Consequential Robotics Ltd. Approximately 400 units have been sold to schools and universities. Working with researchers in Uganda, *Smith* has contributed ML expertise to a project that has rolled out 70 low-cost pollution monitoring stations across Kampala, engaging schools, businesses, civil society organisations and citizens.

In the *dependable and secure systems* theme a key audience is the advanced manufacturing community. A joint appointment with the Advanced Manufacturing Research Centre (*Law*) led to the involvement of AMRC in a TAS Verifiability Node (*Hierons*), engagement in the security of manufacturing robotics (AAIP CSI:Cobot, *Clark*) and a jointly funded PhD studentship (*Popescu*). The University has a dedicated account manager for Siemens; this facilitated the opening of the first MindSphere Lounge in Sheffield and the involvement of Siemens in PITCH-IN (see Section 3.2), which addresses IoT across manufacturing, health, energy, and cities. Research on the security of energy systems with our Department of Civil and Structural Engineering, supported by the EPSRC £34m Active Building Construction project, provides further opportunities for stakeholder engagement.

4.4 Wider contributions to the economy and society

Strategic investment in Faculty marketing resource (14 FTE) enabled us to raise the profile of our research, leading to influence on policy makers. The high media profile of *Bontcheva's* work on fake news led to policy work with the UK government (DCMS report on social media disinformation) and UNESCO (report on COVID-19 disinformation). Our research on the ethics of autonomous weapons has influenced policy within the UN and non-government organisations such as the Campaign to Stop Killer Robots (*Banning LAWS* impact case study).

We achieve broad contributions to the economy through the provision of open-source software. Our GATE text engineering platform is used by Oracle, the BBC, the Press Association and Euromoney. FLAME GPU, a high-performance framework for agent-based modelling, allowed Atkins to achieve an order of magnitude speedup in transport simulations. We expect these advances to be incorporated into the Atkins software used by Highways England.

Our research contributes to public health, both internationally and nationally. *Clayton* has co-authored a research agenda for uncertainty in computational models of cardiac physiology with regulatory scientists from the US Food and Drug Administration. During the COVID-19 pandemic, we were agile and responsive. Working with colleagues from four Chinese universities, *Yang* published a feasibility study of mitigation and suppression strategies for COVID-19. *Richmond* led a national development team working on COVID-19 modelling to inform the Royal Society RAMP initiative, the Scientific Pandemic Influenza Group on Modelling (SPI-M) and the Scottish government. *Wang* contributed to an effort that sequenced more than 1,000 COVID-19 genome sequences, uploading them to the COVID-19 Genomics UK (COG-UK) Consortium and helping researchers around the world to fight the pandemic.

4.5 Engagement with diverse communities and the public through research

We engage citizens in our research through participatory design studies. Examples include an AHRC-funded grant in which a group of cochlear-implanted users co-developed materials for conversational training (*Brown*) and patient involvement in developing technology to diagnose diabetic retinopathy (*Lanfranchi*, *Villa-Uriol*).

Close engagement has been established with the arts around AI, visualisation and sound. *Brown* collaborates with the rock band *Reverend and the Makers* on AI methods for music generation, supported by HEIF funding of £54k. This collaboration was featured in Sheffield's *Sensoria* festival and led to the foundation of a new AI record label. The biennial *Festival of the Mind*, has engaged approximately 103,000 people to date. We have provided exhibits that engage the public in our robotics research (*Prescott*), virtual and augmented reality (*Maddock*), and sentiment analysis

(*Stevenson*). Outside of this festival, our staff regularly engage in "pint of science" pub talks and other events, numbering over 70 in the assessment period.

We have achieved extensive media engagement over the assessment period. *Sharkey* is a strong voice in the debate on the ethics of robotics, AI and data science with frequent media contributions including The Guardian, BBC News and the New York Times. *Lawrence* wrote 11 articles for The Guardian on topics relating to the ethics of AI, open data science and data privacy, shared more than 1500 times via social media and other news outlets. *Marshall's* work on biomimetic robotics has engaged audiences in bee behaviour (BBC Click) and drone delivery (Financial Times, Daily Mail).

We are passionate about engaging young audiences in our research. We host the UK-RAS School Robotics Competition and offered more than 28 talks and events addressed to a school audience over the assessment period. *Prescott's* interdisciplinary research at the boundary of psychology, neuroscience and robotics has engaged children through the Cyberselves Roadshow and Norwich Science Festival.

4.6 Academic leadership and contribution to the sustainability of the discipline

Through our strategy, we are well placed to contribute to the sustainability of the discipline. An example is research by *Marshall*, *Vasilaki* and *Mangan* within our *bioinspired machine intelligence* theme, which promises next-generation AI systems that match insect performance in tasks such as vision and navigation and are power efficient due to having lower computational requirements. We are well placed to develop this theme, with more than £8.9m in funding in place and a route to translation through spin-out Opteran.

We actively engage in setting the national agenda. *Prescott* and *Law* have co-authored EPSRC UK-RAS white papers on robotics in social care and manufacturing robotics, which have been influential in setting EPSRC priorities. Our robotics activity makes us well prepared to respond to initiatives such as the Made Smarter Review, which identified Sheffield Robotics as a "significant contributor and innovator in global robotics research" (p. 66). By growing our *healthcare technologies* and *dependable and secure systems* themes (13 new appointments, see Section 2.2), we have strengthened our research base in areas related to AI and data science for health and to Industry 4.0. This puts us in a strong position to respond to developments in the Industrial Strategy. Our RSE group contributes to the sustainability of the discipline by advocating excellence in research software engineering practice through *Richmond's* leadership positions in the Software Sustainability Institute and the Society of Research Software Engineers (see Section 3.3).

We provide leadership through international steering groups and advisory boards. Six of our staff hold such roles. For example, *Vasilaki* advises the AI Centre at the University of Mainz, Germany. *Prescott* leads a UK-RAS strategic task group on robotics, involving 14 organisations spanning universities, professional societies and the private sector. *Lawrence* has been a member of the AI Council since it was founded in 2019, an independent expert committee advising the government and high-level leaders of the AI ecosystem.

Our staff are active members and leaders of national research networks. We led two EPSRC networks (HealTex, POEMS) and participated in 12 others. *Hierons* is on the BCS-FACS committee and acts as their representative on the LMS Computer Science Committee. Since 2007, *Struth* has co-organised the Midlands Graduate School (MGS) in the Foundations of Computing Science, involving the Universities of Sheffield, Leicester, Nottingham, and Birmingham. *Moore* and *Hain* make significant contributions to international leadership of the SLT community as board members of the International Speech Communication Association (ISCA).

The Gaussian Process Summer School, run by *Lawrence* and *Alvarez* since 2013, has become a staple of PGR training and attracts industry delegates from Amazon, Spotify, JPMorgan, Siemens Gamesa etc. Data Science Africa, an annual series of workshops led by *Lawrence* and *Smith* since 2015, has brought together academic and industry experts in data science and ML to deliver research training across Kenya, Uganda, Tanzania, Nigeria, Ghana and Ethiopia.

Our staff make outstanding contributions to international science publications. They hold 20 editorial positions**,** including 3 Editor-in-Chief positions, e.g. *Moore* is editor-in-chief of *Computer Speech and Language*, a key journal in the area of SLT. During the assessment period, 33 of our staff were involved in organising conferences, with 17 acting as Programme Chair. *Lawrence* was General Chair of the influential NeurIPS conference (2015) and *Hain* was Technical Chair of the Interspeech conference (2019).

12 of our staff provided leadership as full members of the EPSRC college, three of which are associate members. 9 colleagues sat on grant panels, 4 as chair. *Vasilaki* and *Clark* were in the top 6% of college members for participating in peer review activities during the academic year 2017/18. Our staff were external examiners for theses and habilitations in more than 40 institutions across 11 countries, including several prestigious universities (e.g. Sorbonne, Oxford, Cambridge, La Sapienza).

The esteem and success of our staff are reflected by the award of many prizes and honours, including 24 keynotes/invited talks and 7 fellowships since REF2014. *Hain* was elected a Fellow of the ISCA, and *Moore* is a Distinguished ISCA Lecturer. 14 staff members are members or fellows of professional societies.

We are immensely proud of our contributions to computer science, our productive engagement with the end users of our research, and our success in communicating our exciting findings to the public. Since 2014 our growth has delivered an outstanding complement of staff and increased our momentum. With a clear strategic plan, we are well placed to build on our strengths over the next decade and make further significant contributions to the discipline, economy and society.