Institution: University of Liverpool

Unit of Assessment: 11 (Computer Science)

1. Unit context and structure, research and impact strategy

1.1 Overview of Unit structure

The Department of Computer Science is part of the School of Electrical Engineering, Electronics, and Computer Science (EEECS) within the Faculty of Science and Engineering. The department's research is organised around four closely interlinked research clusters:

- Algorithms and Networks (ALGO, 10 faculty).
- Artificial Intelligence (AI, 11 faculty).
- Economics and Computation (EcCo, 10 faculty).
- Logical Methods in Computer Science (LMCS, 11 faculty).

ALGO, LMCS, and EcCo are three of the largest research clusters in the world in their respective fields, and have a long history within the department going back 25, 19, and 10 years, respectively. AI, with its focus on Machine Learning and Argumentation and applications in Autonomy, Natural Language Processing, and Legal Systems, is a more recent strategic addition to the department. It was formed in 2015 as an evolution of our Multi-Agent Systems research group. Each cluster grew during this REF period, primarily through the hiring of 14 early career researchers that provide vitality and fresh ideas.

The purpose of the clusters is to coordinate research collaborations and provide an interface to the university and the outside world. Below research clusters, the department is structured` into seven research groups, which exist for organisational purposes, for example, for mentoring and specialised seminars. Each research group contributes to multiple research clusters, with the structure and interconnections shown in Figure 1 below, which also shows interdisciplinary centres, centres for doctoral training, and stakeholders from elsewhere in the university. This figure is explained in more detail later and is used throughout the document.

1.2 Research and Impact Strategy

Our three objectives are to:

- Compete and collaborate with the leading Computer Science departments in the world in our core research areas.
- Apply our research for the benefit of the economy and society, in Merseyside, the UK, and across the world.
- Support the next generation of computer scientists (ranging from PhDs to ECRs), and help them to reach their potential as the future research leaders of their respective fields.

Our research strategy to achieve these objectives has been to develop:

RS1: *Core Strengths.* Invest in carefully selected areas of existing strength and future potential within our four research clusters, Algorithms, Artificial Intelligence, Economics, and Logic. To illustrate, since 2017 we have hired at least three ECRs in each of the clusters, each adding strength in areas identified as strategically important.

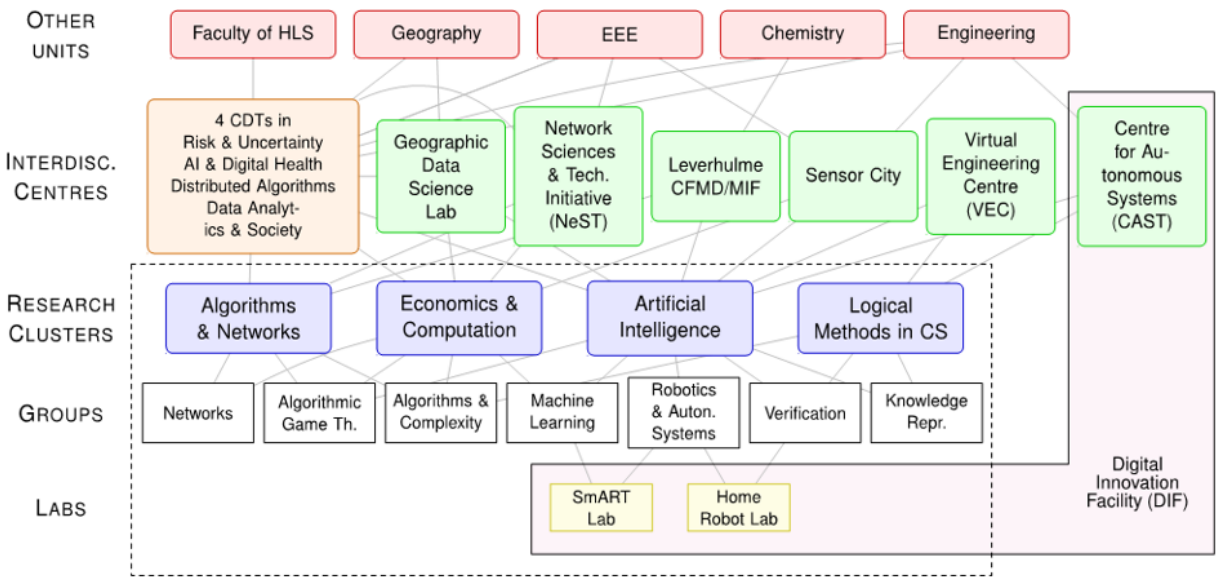
RS2: *Interdisciplinarity.* Collaborate with other disciplines to realise the potential of our research beyond our core research areas, for example, through interdisciplinary centres such as the Centre for Autonomous Systems, the Leverhulme Centre for Functional Materials Design, Sensor City, and the Virtual Engineering Centre.

RS3: *Targeted Impact.* Introduce specific mechanisms to translate our research expertise into work that directly addresses economic and societal challenges; in particular, we aim to:

1. Support and develop new and existing collaborations with non-academic partners, for example, via Knowledge Transfer Partnerships (KTPs) and interdisciplinary projects (RS2).
2. Support public engagement, for example, to raise public understanding of safety and trustworthiness of AI systems.

RS4: *New Talent.* Invest in developing new talent in computing, ranging from PhD students to ECRs. To illustrate, the number of PhD students that have graduated has increased by more than 150% compared to the last REF period.

RS5: *People.* Develop further our emphasis on equality, diversity, and well-being. Ensure that our research environment embodies the principles of the Researcher Development Concordat and Athena SWAN. For example, the proportion of female PDRAs has increased from 15% in REF2014 to 25% during this REF period.



Glossary:

CFMD	Leverhulme Centre for Functional Materials Design
EEE	Electrical Engineering and Electronics
HLS	Health and Life Sciences
MIF	Materials Innovation Factory

Figure 1. The unit and its major connections within the university.

To ensure accountability, participation, and transparency, our research strategy is reviewed and discussed in research cluster and department-wide meetings, including our annual department away day. The overall strategy is agreed and executed by the departmental research committee, consisting of the Head of Department, the Deputy Head of Department for Research, the Heads of the Research Clusters, and our Impact Facilitators.

RS1, RS2, and RS3 were at the core of our future strategy in REF 2014. They were revisited, reconfirmed, and then fleshed out early during this REF period. For example, the unit developed RS3.2 since we believe that our research and commercial impact activities in AI should be complemented by raising public understanding of AI technologies. RS4 and RS5 recognise that to reach our main objectives in a rapidly developing and highly competitive discipline such as Computing, we have to invest in new talent, while creating a supportive environment for all staff and students. RS1–RS5 are discussed further throughout the document.

1.3 Implementation and Achievements

Figure 2 evidences the success of the unit's strategy for growth. In line with RS4 (*New Talent*), this growth includes 14 new ECRs. We report in detail on the implementation of RS4 and RS5 (*People*) in Section 2, and on research income in Section 3. We next give details of our implementation of RS1, RS2, and RS3.

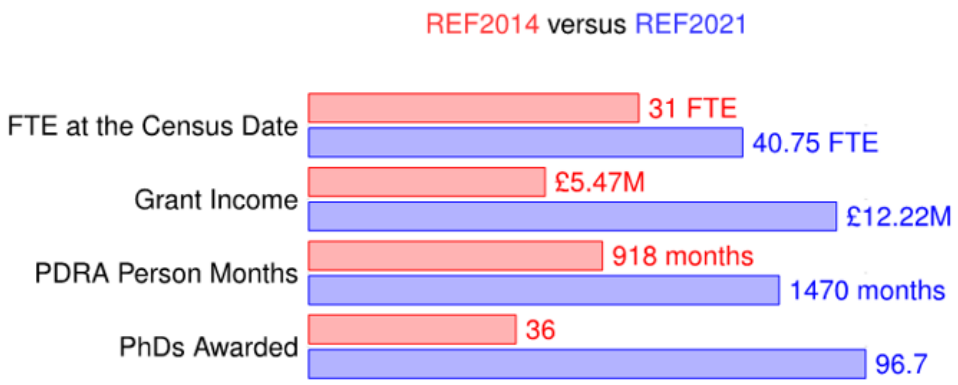


Figure 2: Growth since the last REF (with all eligible FTE counted for REF2014).

RS1 (*Core Strengths*)

We organise our research around four research clusters, which all have critical mass at all levels of seniority and are appropriately supported by research funding. We aim to empower staff to develop and realise their own research agenda. Collaborations across clusters are encouraged and indeed fundamental to our approach. We summarise the research achievements of our clusters below.

Algorithms and Networks:

This cluster addresses emerging research challenges in networks and distributed computing, graph theory, scheduling, reachability, and, more recently, the underpinning area of data structures and complexity theory. It publishes regularly in the core venues of the field, for example a combined total of 59 papers in Algorithmica and TCS during this REF period. The unit is a founding member of the EPSRC AlgoUK Network for Algorithms and Complexity in the UK (2017–).

The cluster hosts the Network Sciences and Technologies Initiative (NeST; see Figure 1). Within NeST, Gasieniec, Michail (ECR), Spirakis, and Zamaraev (ECR) have initiated the study of temporal graphs, an extension of graph theory suitable for representing modern dynamic systems. The cluster also continued its long research tradition in distributed computing, for example winning a Best Paper Award at ICALP'18 (Kowalski), and achieving breakthroughs in population protocols (Gasieniec, JACM'20). Potapov's research in reachability problems for words and matrices was recognised by the award of a Royal Society Leverhulme Trust Senior Research Fellowship.

Another focus of the cluster is scheduling theory (Christodoulou, Kowalski, Wong), with contributions ranging from efficient scheduling solutions for smart power grids to substantial progress on the Nisan-Ronen conjecture (STOC'20).

In addition to the ECRs hired in networks, the cluster made the strategic decision to invest in complexity theory and data structures, and recruited Ikenmeyer (from Simons Institute Berkeley and Max Planck Saarbrücken) and Tsakalidis and Wild (both ECRs from University of Waterloo), respectively.

Economics and Computation:

This cluster addresses research challenges in algorithmic game theory and mechanism design, and published 32 papers at the three key specialised venues (EC/SAGT/WINE) during the REF period. The cluster also brought the SAGT conference to Liverpool in 2016.

Christodoulou, Gairing, Sgouritsa (ECR), and Spirakis have made ground-breaking contributions

in the area of quality of equilibria, for example, by initiating the study of the Price of Anarchy of auctions (JACM'16), designing networks with good equilibria (SICOMP'19), and resolving the long-standing open question of the Price of Stability in Weighted Congestion Games (SICOMP'19). Christodoulou was supported by a Royal Society Leverhulme Trust Senior Research Fellowship.

The cluster has made numerous contributions in the area of mechanism design, including on pollution control and mechanism design with verification (Krysta JAIR 2018, Algorithmica 2019). On the complexity of equilibria, Fearnley and Savani resolved fundamental questions about the complexity of linear programming (STOC'15), strategy improvement (SODA'16), and the query complexity of equilibria (Algorithmica 2019).

In addition to Fearnley and Sgouritsa, the cluster made three further strategic hires, Filos-Ratsikas (ECR, from EPFL Switzerland), Ibsen-Jensen (ECR, from IST Austria), and Laraki (Reader, from Ecole Polytechnique), who strengthen our expertise in complexity of equilibria, stochastic games, and voting theory.

Artificial Intelligence:

This cluster addresses research challenges in autonomous systems, argumentation, and multi-agent systems, and has strategically expanded into machine learning and data mining and its applications in NLP, vision, and robotics. Over the REF period, the cluster has published a combined total of 68 IJCAI and AAAI papers, and a combined total of 16 AIJ and JAIR papers.

The cluster led the EPSRC-funded UK Network on "Verification and Validation of Autonomous Systems" (2015-19), and pioneered the use of formal verification for the safety and reliability of autonomous systems and robotics. The AI cluster also hosts two robotics labs, the smARTLab and Home Robots Lab; see Figure 1.

The unit has continued to be an international centre for computational argumentation and its application to AI and Law. Over the REF period, research by Atkinson, Bench-Capon (emeritus), and Dunne led to a combined total of 30 papers in COMMA/JURIX/ICAIL, the main venues for research in the area.

Bollegala and Goulermas (who joined the unit in 2015) are leading the machine learning activities of the cluster, with Bollegala (Amazon Scholar since 2019) focusing on NLP applications, in particular word embeddings (TKDE 2016), and Goulermas working on representation learning and combinatorial data analytics (TPAMI 2015, 2017).

Over the REF period, the cluster expanded into computer vision and robotics by recruiting the ECRs Lu (Oxford), Luo (Harvard and Leeds), and Do (University of Singapore). Luo is now leading the smARTLab.

Logic:

This cluster addresses research challenges in the logical foundations of computing, automated reasoning, formal verification, and knowledge representation. Over the REF period, the cluster has published a combined total of 33 papers in LICS/LMCS/InfoComp, the core venues for logic in computer science.

Fearnley, Schewe, and Wojtczak have made significant progress on fundamental questions in optimal control, strategy generation, and solving multi-player games. In the same area, the cluster hosted Marie Skłodowska Curie Fellows Hahn and Lehtinen (ECR). Hernich, Konev, and Wolter worked on logical methods for ontologies and ontology-based data management, winning distinguished paper awards at PODS'17 and IJCAI'18.

The work of Hustadt on calculi for modal logics was invited to the Best Papers from Sister Conferences Track at IJCAI'17. Kuijer (ECR), Van der Hoek, and Wojtczak have investigated logics for gossip protocols (JAIR'18 and AIJ'20). Another highlight is the application of SAT solvers to the Erdős Discrepancy Conjecture (AIJ'15) by Konev and Lisitsa that has been celebrated in academia and the media (for example, the Independent and New Scientist).

In addition to the two ECRs mentioned above, the cluster has strengthened its expertise in logical and automata-theoretic foundations of verification by recruiting Totzke (ECR from Edinburgh) and Zimmermann (from Saarbrücken).

Inter-cluster collaborations:
Cross-cluster collaboration is fundamental to our research culture, and many staff contribute to two or more clusters. One important interface is between logic and AI, where we apply logical methods to verify and increase the trustworthiness and safety of AI systems. In the REF period we have recruited Huang (ECR from Oxford) who has pioneered the verification and testing of deep learning algorithms (CAV'17). Others working at this interface include Van der Hoek, Kuijer, Luo, and Wolter. The AI, Algorithms, and Economics clusters have collaborated extensively to make progress in understanding automated markets – ranging from online retail and internet advertising to automated trading in financial markets. The unit also recruited Kurlin (Durham), whose work bridges AI and Algorithms to support materials design, as discussed further below.

RS2 (*Interdisciplinarity*)
To realise the potential of our research beyond our core research areas, the unit has taken leadership or major roles in expanding existing interdisciplinary centres, while also developing new ones; see Figure 1.

- **The Leverhulme Research Centre for Functional Materials Design (CFMD)** opened in 2017 with £10M of funding to last until 2027. It is a collaboration between Computer Science and Chemistry. The main computing topics are Computational Materials Design (Krysta, Michail, Potapov, Spirakis from NeST), Intelligent Automation (Atkinson, Tuyls), and Harnessing Exponential Knowledge Growth (Goulermas, Kurlin).
- **Sensor City** opened in June 2017. It is a £15M joint venture between Liverpool John Moores University and The University of Liverpool. Computer Science collaborates with Sensor City on a range of applications of AI to secure and wearable sensors (Coenen, Gairing, Savani).
- **The Centre for Autonomous Systems Technology (CAST)** was a key part of our REF2014 impact strategy. CAST is led by the unit (Fisher until 2020, now Huang) and coordinates activities across the university in software autonomy, verification, and trust. It has grown significantly during this REF period, funded through three Robotics and AI Hubs and four EPSRC projects (£5.75M in the unit).
- **The Virtual Engineering Centre (VEC)** was founded in 2010. It currently employs 22 staff, and has a turnover of approx. £2.5M. A prominent example of a Computing/VEC collaboration is the GAMMA EU Project (Growing Autonomous Mission Management Applications), which ran from 2012 to 2020.

These centres are supported by the university as part of the two university-wide themes, Digital (all centres) and Advanced Materials (CFMD). The centres are complemented by a wide variety of interdisciplinary research projects. As planned in our REF 2014 future strategy, we have worked closely with our sister department EEE. We give two examples: the Algorithms cluster runs NeST jointly with Marshall's networking group; collaboration between the unit and Maskell's group underpins our CDT in Distributed Algorithms, and, along with Medicine, the large EU WEB-RADR project on studying adverse reactions to pharmaceutical drugs. In line with RS3.1, and envisioned in our REF 2014 future strategy, interdisciplinary projects have been a path to impact. This is illustrated by two of our returned impact case studies:

- The Geographic Data Science Lab (GDSL) is a multi-faceted collaboration between Computer Science and Geography (see Figure 1). The impact, which is underpinned by GDSL's methodology for creating geodemographic classifications, has beneficiaries that range from Hull City Council to the Anti-Eviction Mapping project in the US.
- LiftUpp is an assessment information system for clinical education that was developed jointly by Computer Science (Jimmieson, Savani) and the Dental School (Dawson) at University of Liverpool. It is used by 63% of dental schools in the UK.

Further details and other examples of interdisciplinary activities are given in later sections.

RS3 (*Targeted Impact*)
Interdisciplinarity is complemented by the following mechanisms to encourage and support the development of impact. Our *Impact Facilitators* run departmental impact workshops, visit research groups, and support impact-related funding applications. The impact workshops are often attended by existing and potential non-academic partners. They present developing impact cases, along with new challenges and potential collaborative projects. The department's Industrial Liaison Committee (ILC) comprises a mix of representatives from large corporations such as IBM, Unilever, and PwC, and local SMEs. The ILC reviews and informs our impact strategy.

We next discuss the achievements of our strategy in relation to the two points of RS3.

RS3.1: New and existing collaborations with non-academic partners.
The unit has forged many new collaborations with non-academic partners during this REF period. This was facilitated by 10 Knowledge Transfer Partnerships (total funding of £2.4M) and 25 direct industry projects and consultancies; further details can be found in Section 3. For example, our "nDrites: Enabling Laboratory Resource Connectivity" impact case study was the outcome of a KTP with a local SME, CSols. In this KTP, Atkinson, Coenen and Payne developed an agent-based technology that is widely used by utility companies for monitoring drinking water quality.

Impact arising from interdisciplinary projects has been discussed above. Our interdisciplinary Centres for Doctoral Training (CDTs) are another pillar of our engagement with non-academic partners. The unit is a major stakeholder in 4 industry-focused CDTs. Every centre PhD project involves a non-academic partner, including, for example, IBM, Roche Diagnostics, and Unilever. We give more details on these CDTs in Section 2 under PhD training; also see Figure 1.

RS3.2: Public engagement.
During the REF period, the unit made a targeted and concerted effort to engage the public in the areas of AI and Robotics, Trustworthiness of AI systems, and AI and Law (Atkinson, Collins, Dennis, Fisher, Tuyls). Our outreach impact case is based on our engagement with schools in the North West and the university's partnership with the Tate Gallery, which led to the "Sprung a Leak" installation on robotics that has travelled from Tate Liverpool to Belgium, Germany, and Japan. Atkinson's invitation to deliver part of the 2019 Royal Institution Christmas lectures was based on the unit's standing in the field of AI and Law.

1.4 Strategic research and impact aims for the next five years

In 2020 we revisited our objectives and strategy and decided that our three objectives will remain unchanged over the next five years. At the strategy level, we will adjust RS1 (*Core Strengths*) and RS2 (*Interdisciplinarity)* by developing further our inter-cluster activities, with emphasis on three key areas:

- **Verification of AI.** The unit has pioneered logic-based methods to ensure the safety, interpretability, and trustworthiness of AI systems. Following the departure of Dixon and Fisher, we will strengthen this area by advancing approaches that bridge the methodology gap between symbolic and sub-symbolic AI. This will be led by Huang, Luo, Schewe, Wojtczak, and 3 new lectureships.
- **AI and Law.** This theme is at the intersection of argumentation, multi-agent technologies, and NLP (Atkinson, Bollegala, Coenen). We will build on our existing strength and put the unit at the centre of a Liverpool-based legal technology hub.
- **Automated Markets.** We will address important emerging themes such as the regulation of competing strategic algorithmic agents in financial and retail markets (Christodoulou, Filos-Ratsikas, Savani, Sgouritsa).

These and related activities will be supported by the new **Digital Innovation Facility** (DIF) which is discussed in more detail in Section 3. It will house CAST, the smARTLab, the Home Robots Lab, a branch of the VEC, along with many SMEs. Our leadership in the DIF will be complemented by continued support and growth of the interdisciplinary centres during this REF period. The DIF will also support our implementation of RS3 during the next REF period.

RS4 (*New Talent*) of our strategy has been successfully implemented during the current REF period. Over the next REF period, we will put even more emphasis on hiring female academics, discussed in more detail in Section 2. Within RS5 (*People*), an important focus will be developing our 14 ECRs.

1.5 Research Integrity and an Open Research Environment

The unit embraces an ethical approach to research, and views an open research environment as a key component of research integrity. To illustrate, we have contributed to the development of standards and professional frameworks to ensure the ethical use of AI in autonomous systems and robotics (see Section 4), and the unit has contributed to an open and informed discussion with the public about the impact of AI on society (as described in one of our impact cases). These activities are informed by the unit's research on explainable AI (Huang), the application of AI to the legal sector (Atkinson), and trust in and the ethics of AI (Dixon/Fisher).

In line with the institution's policy, the unit is committed to providing a rigorous and independent process of ethical review. To this end, the unit has a dedicated Ethics Officer (Biktasheva), who advises on ethical aspects of research projects and on processes for seeking ethical approval. Every staff member takes the university-produced "Research Ethics Training" online module.

The unit regards reproducibility of research as a precondition for both integrity and openness. Reproducibility requires free access to papers, code, and data:

Papers.
The unit aims to make all its research available to anyone for free by making extensive use of the open publishing service arXiv (> 450 papers on arXiv during this REF period) and the institution's research repository for papers.

Code.
The unit strives to make all software and code related to our research freely available. For example, the Economics cluster provides the web-based software platform "Game Theory Explorer" to the research and teaching community; its source code is freely available on github, as is our work on Natural Language Processing (https://github.com/LivNLP), and our work with the Leverhulme Research Centre for Functional Materials Design (https://github.com/lrcfmd).

Data.
Where data is used in our research, we either use external publicly-available datasets, or, where licensing conditions permit, make our data publicly available. For example, much of our work with the Geographic Data Science lab uses the data repositories of the Consumer Data Research Centre hosted at Liverpool (http://cdrc.ac.uk).

In terms of training and guidance for reproducibility, the unit participates in N8 CIR ReproHacks, which are one-day reproducibility hackathons; the February 2020 event was held at Liverpool.

2. People

Guided by point RS5 (*People*) of our overall strategy, we have developed further our emphasis on equality, diversity, and staff well-being and have applied the principles of the Researcher Development Concordat to all research-active members of the department. Guided by point RS4 (*New Talent*), recruitment has focused on attracting excellent early career researchers, PDRAs and PhD students. In this section, we discuss in detail our staffing strategy, staff development, and research students. We discuss equality and diversity issues throughout the section, with a dedicated final section that deals with EDI issues not covered elsewhere.

2.1 Staffing Strategy

The department has expanded considerably during the REF period: 20 new members of staff have been hired. In line with point RS4 of our research strategy, we have focused on hiring early career researchers. In fact, over the REF period the department did not recruit at all at professorial level, while at the same time, we recruited 15 lecturers, 1 lecture-track fellow, 2 senior lecturers, and 2

readers; 6 existing members of staff were promoted to professor, 6 to reader, and 7 to senior lecturer. In short, our staffing strategy has followed the principle of "We don't buy stars, we make them".

The following hires were made during the REF period, at lecturer level unless indicated otherwise. All lecturers except Fearnley and Zimmermann are ECRs.

- Ikenmeyer (SL), Michail, Tsakalidis, Wild, and Zamaraev have joined Algorithms and Networks.
- Fearnley, Filos-Ratsikas, Ibsen-Jensen, Laraki (Reader) and Sgouritsa have joined Economics and Computation.
- Goulermas (Reader, now Professor), Kurlin (SL), Lu, Luo, and Do have joined Artificial Intelligence.
- Huang (now Reader), Kuijer, Lehtinen (Lecture-track Fellow), Totzke, and Zimmermann have joined Logic.

We are proud to have been able to attract these excellent researchers. To illustrate, Wild won the 2016 Best German-Swiss-Austrian Dissertation Award in Informatics for his work on sorting algorithms and Sgouritsa was runner up for the 2018 BCS Distinguished Dissertation Award for her work on algorithms for game-theoretic environments. All hires are in line with RS1 (*Core Strength),* and we have described in Section 1 how these new recruits fit into our research clusters.

The strategic thinking behind the more senior hires was the following. Ikenmeyer brings new and complementary strength to the algorithms cluster. He is a world-leading expert on complexity theory, with 7 STOC and FOCS papers and support from a German DFG project (EUR 356K). Kurlin works at the intersection of computing and materials science. In line with RS2 (*Interdisciplinarity*), Kurlin strengthens our collaboration with the Materials Innovation Factory (MIF), discussed in detail in Section 3. Goulermas is an expert in machine learning and has been leading industry projects (for example in health, law, and defence) for over ten years. Jointly with Bollegala, Goulermas provides leadership to the Machine Learning group. Laraki is an expert in the theory and practice of voting, complementing existing strength in the EcCo cluster. He is the author of three Economics monographs and Fellow of the Game Theory Society. Laraki's voting method majority judgement is having significant non-academic impact (see Section 4), supporting RS3 (*Targeted Impact*).

We have a balanced profile of faculty: 14 professors, 5 readers, 4 senior lecturers, 18 lecturers, and 1 lecture-track fellow. Every research cluster is led by 3-4 professors and has 4-5 lecturers, and thus has a good mix of seniority levels.

We have implemented the Concordat's principles for recruitment. We aim to attract the best researchers by advertising widely, and involving research groups in actively soliciting applications. We strongly encourage applications from candidates with diverse backgrounds. In particular, actions have been taken to systematically improve the numbers of BAME and female staff that we recruit. For example, at least one female candidate is short-listed for each vacancy, interview panels include at least one female member, and advertisements are reviewed to ensure that Athena SWAN principles are included. In the current REF period, we hired four BAME ECRs (Luo, Lu, Huang, and Do) and two female ECRs (Lehtinen and Sgouritsa).

2.2 Staff Development

We recognise that staff need time, space, and support to deliver world-class research and impact. Facilitated by the creation of 5 offices during the REF period, all faculty have their own offices, all within one building. Teaching loads for research active staff are uniformly light, not exceeding two modules per annum. This has been partly enabled by the employment of 5 permanent teaching fellows and the support of 4 technicians. We also use sabbaticals and part-time working arrangements to give staff time for research and impact activities. Applications for a sabbatical are open to all, and assessment of applications takes EDI considerations into account. In this REF period, 8 academic staff took sabbaticals. These staff span different levels of seniority, gender, and other protected characteristics. Examples include establishment of industry collaborations

(Tuyls, Google DeepMind), completion of long-term collaborative research projects (Christodoulou, Biktasheva, Wojtczak), and development of collaborative grant proposals (Spirakis). Part-time working arrangements over the REF period have allowed Bollegala to collaborate with Amazon, Japan, and Laraki (50% Liverpool) to continue his CNRS position at LAMSADE, Paris.

Promotion.

Promotions are awarded through the University's annual review procedures, independent of the unit. Evidence of the success of the unit's staff development approach includes the large number of promotions, nineteen, within the REF period. This includes three female staff (Atkinson - promoted to Dean of School, Dixon and Wong) and three BAME staff (Bollegala, Savani, Wong) promoted to professor, compared with only one female professor and only one senior BAME academic in 2014.

Early career researchers.

Early career researchers form a key part of RS4 (*New Talent*), and so the department has extensive support for ECRs to help new members of staff establish their research careers.

Reduced load.

In their first year, ECRs teach at most one module, do not first supervise any final-year projects, and normally have no administrative duties. Their load gradually increases over their first three years.

Dedicated mentor.

Every ECR staff member is assigned a senior academic from the department as a mentor. Mentors give advice on a wide range of topics including teaching, research, and career progression.

Support for grant applications.

In addition to the general support discussed in Section 3, the unit created the "Get the Grant" initiative specifically for ECRs. The initiative is led by Schewe and includes regular workshops and talks by funding organisations.

Integration activities.

New academics are invited to present their research at the annual departmental away day, at departmental seminars, and at the industrial liaison committee.

To give an example of where the measures helped an ECR to establish their career through funded research projects, Luo arrived in 2018 from Harvard. Since then, he won an award from the Centre for Digital Built Britain to work on "Aerial Swarm Robotics for Active Inspection of Bridges" (PI), a UKRI/AHRC grant to work with the Shanghai Theatre Academy on "Shaun the Sheep: Immersive Experience" (co-I), and an EPSRC New Investigator Award to work on "ViTac: Visual-Tactile Synergy for Handling Flexible Materials". Another example of an ECR who won an EPSRC New Investigator Award is Totzke with his project "The Cost of Winning Strategies".

PDRAs.

In line with RS4 (*New Talent*), PDRA activity has risen from 918 PDRA person months in the last REF period to 1470 in this period, with an accompanying improvement in PDRA gender balance, from 15% female in the last period to 25% in this one. As members of academic staff, PDRAs are fully integrated into our research groups and environment. In addition to the standard support mechanisms given to all academic staff (for example, personalised induction, training, annual PDR, reviewing of grant proposals), PDRAs are members of the School PDRA forum, which meets regularly to discuss PDRA-specific matters and represents the PDRAs at unit and school (EEECS) level. The unit supports fellowship applications of PDRAs via mentors and match funding commitments. As an example of success, Lehtinen secured a Marie Skłodowska Curie Fellowship while a PDRA in the unit and stayed as a lecture-track fellow.

As an indication of the success of our PDRA support, during this REF period the following PDRAs progressed on to permanent teaching and research positions: Fearnley and Kuijer (Liverpool), Deligkas (Royal Holloway), Akrida (Durham), Gutiérrez Basulto (Cardiff), de Keijzer (King's College London) and Slavkovik (Bergen). Deligkas and Akrida also attained their PhDs in the unit.

Many other PDRAs have gone to successful careers in industry, for example, Riley (Head of Innovation at the Quant Network), Cucco (Global Robotics and Automation Engineer, Unilever), and Caliskanelli (UK Atomic Energy Authority).

2.3 Research Students

As part of our commitment to developing the next generation of Computer Science researchers in point RS4 (*New Talent*) of our research strategy, we have dramatically expanded our training of postgraduate research students, with over 96 students graduating in the current REF period compared to 36 graduating previously. We are proud of the fact that 35% percent of these graduated PhD students are female.

The growth in PhD student numbers was enabled by the strategic decision of the School of EEECS to internally fund 10 PhD students a year, with allocations decided by: the quality of the candidates, the strategic fit of the project, a preference for an ECR on the supervisory team, and careful consideration of equality and diversity, including protected characteristics of the candidates. In addition to the internally-funded students, the growth in PhD student numbers was supported by four doctoral training centres which we discuss next.

Centres for Doctoral Training.
The department is heavily involved in four doctoral training centres: an EPSRC-funded CDT on Distributed Algorithms, an EPSRC/ESRC-funded CDT on Risk and Uncertainty, an ESRC-funded CDT on Data Analytics and Society, and an internally-funded doctoral training programme on AI for Future Digital Health that is led by the unit. Combined, these CDTs have funded 20 PhD students during the assessment period. In line with our commitment to RS2 (*Interdisciplinarity*), all four centres are interdisciplinary. In line with RS3 (*Targeted Impact*), all have significant industry involvement. CDT students are co-supervised by staff members from multiple departments, see Figure 1. Our doctoral training centres have also been a major driver of engagement with non-academic partners, which is discussed in more detail in Section 4.

Training, monitoring, and progression.
Every student is assigned at least two supervisors, and two advisors, who provide additional support and advice. All PhD students are members of the university-wide Liverpool Doctoral College, which offers a wide range of training events including a three-day career-related workshop. Additionally, the school of EEECS runs a series of 20 doctoral training seminars each year, with specific training and advice. Students are encouraged to apply for internships during their PhDs. Examples during this REF period include Butterworth (NNAISENSE, Switzerland), Evangelopoulos (IBM, Daresbury), O'Neill (Amazon, Tokyo), and Spooner (JP Morgan, London).

Evidence of Success.
Our PhD students regularly co-author high quality CS outputs, for example 7 ICALP, 7 Algorithmica, 5 IJCAI, and 6 AAAI papers during the REF period. More than 50% of our graduates now hold positions at CS departments (ranging from UK universities such as Imperial and Oxford University to European universities such as TU Vienna and TU Munich) either as PDRAs, or as academic faculty, such as our female graduates: Liu (Utrecht), Ozaki (Bergen), and Sgouritsa (Liverpool). Many other students that graduated during this REF period have moved to highly competitive jobs in industry, for example, Farrugia (Capgemini), Gatens (ARM), Geleta (Astra Zeneca), Igwe (Hitachi, Japan), and Rajendran (KPMG).

2.4 Equality and Diversity

Earlier in this section we discussed several aspects of RS5 (*People*), for example, study leave via sabbaticals, flexible working arrangements, the promotion of female and BAME staff to professors, and EDI aspects of recruitment. In this subsection we discuss governance, wellbeing, and EDI considerations in relation to the REF exercise itself. We close with an outlook for the next REF period.

Governance and policies.
The University of Liverpool is a member of the Athena SWAN Charter (Institutional Silver Award), a Stonewall Diversity Champion (Top 100 in 2013 and 2014 Workplace Equality Index), and a member of the Two Ticks guaranteed interview scheme. Equality, Diversity and Inclusion principles

have been firmly embedded in our everyday practices.

Within the unit, RS5 (*People*) is overseen by the School Diversity and Equality Committee. Representatives of this committee contribute to the development of all departmental policies, including research policy. Early career researchers have a say on all departmental matters ranging from the newly developed work allocation model (Kuijer), to our mock grant funding panels, and the REF Selection panel (Huang, Sgouritsa).

Wellbeing.
The unit operates policies that provide support for family-friendly working arrangements; these include scheduling of meetings only during school-friendly 'core' hours. Our centralised timetabling system allows for specification of lecture times and dates to provide carer and family-friendly timings. The University provides carer-only car parking to support flexible working. The unit has always supported family leave for staff. In 2016, the School of EEECS introduced a family leave policy for PhD students too, guaranteeing provision for family leave for all research-active members of the department. Over the REF period, ten members of the department took family leave following the birth of children; all were integrated back into the unit successfully.

New staff are offered advice on housing and schools during induction. The unit organises social events for staff and students, including a monthly coffee morning, a summer barbecue, graduation party, special events for major staff anniversaries and awards, as well as an end of year celebration.

Preparation of the REF submission.
The unit implemented the institution's Code of Practice for REF. Outputs of academic staff were peer reviewed by a REF reading group consisting of five academics, which comprised at least one female academic, one ECR, and one BAME member of staff. The members of the panel undertook Advanced HE training in Equality, Diversity, Inclusion, and Unconscious Bias.
Oversight of the selection of outputs, impact cases, and the environment statement was undertaken by the unit's REF Selection panel, which comprised the Department Head, the Deputy Head of Department for Research, an impact facilitator, a member of the School Diversity and Equality Committee, 2 ECRs, and an independent observer from another unit. The REF selection meetings started by viewing and discussing the Royal Society videos on 'Understanding Unconscious Bias' and 'Making better decisions in groups'.

2.5 Outlook and Plans.

In Section 1.4, we outlined research areas for future investment. For the recruitment aspect of this investment, we aim to hire a significantly larger proportion of female academic staff than in the current REF period. One reason for optimism is the proportion of female PDRAs (25%) and female PhD graduates (35%) in the unit. Some of the measures described at the end of Section 2.1 were only implemented in the second half of this REF period and we are confident that they will be effective in the next REF period.

3. Income, infrastructure and facilities

This REF period saw significant strategic growth of 33% in the number of faculty in the unit. To achieve our overall aims, and as previously laid out in our strategy from REF 2014, we have made a concerted effort to grow our complementary research resources: our external research income has grown by 123%, the number of PDRA person months by 60%, and the number of PhD students by more than 150%. To support this growth, we have invested in infrastructure such as office and lab space, new interdisciplinary centres, and high-performance computing facilities.

3.1 Research Funding and Strategy

Our funding strategy is guided by RS1 (*Core Strengths*), RS2 (*Interdisciplinarity*), and RS3 (*Targeted Impact*) of our overall research strategy. For RS1, we typically target funding for PDRAs via mid-sized multi-site research council grants in our core research areas of Algorithms, Artificial Intelligence, Economics, and Logic. For RS2, we encourage and support participation in large

interdisciplinary projects, both with other parts of the university (see Figure 1) and with other universities, institutes, and commercial partners. For RS3, we promote joint projects with non-academic partners, such as Knowledge Transfer Partnerships (KTPs), as a mechanism to achieve impact.

The School of EEECS has a dedicated research support officer, whose responsibilities include distributing funding calls and supporting grant writing and costing. The school also runs a mock grant funding panel every two to three months at which proposals are reviewed and discussed with applicants. For KTP applications, the UoA has established an internal support network (led by Coenen).

We next describe our achievements and plans related to RS1 to RS3.

RS1 (Core Strengths):
We provide highlights of externally-funded research in our four core research areas.

Foundational research in temporal graphs and reachability by Michail, Potapov, Spirakis, and Zamaraev was supported by EPSRC projects *Algorithmic Aspects of Temporal Graphs* and *Reachability problems for words, matrices and maps: Algorithms and Complexity* (total £965k). These grants supported Liverpool's leading role in these areas, including the Reachability Problems conference series organised by Potapov and the series of workshops on temporal graphs at ICALP organised by Spirakis, Zamaraev, and others.

In the area of trustworthy and explainable Artificial Intelligence, the unit's logic-based approach was first led by Dixon and Fisher, supported by the following EPSRC grants: EPSRC Programme Grant *Science of Sensor System Software* (£5.24M, UoA £1.1M), EPSRC projects *Reconfigurable Autonomy, Trustworthy Robotic Systems*, and *Verifiable Autonomy* (total £1.8M). Based on this research, Fisher was awarded a Royal Academy of Engineering Chair in Emerging Technologies (£2.7M). Since his arrival in 2017 as an ECR, Huang has extended this approach to the verification of machine learning algorithms, supported by 4 Dstl projects, an EPSRC project *EnnCore: End-to-End Conceptual Guarding of Neural Architectures* and a Horizon 2020 EU project *FOCETA - Foundations for Continuous Engineering of Trustworthy Autonomy* (total £1.8M for the UoA).

Liverpool's leading role in research at the interface of knowledge representation and databases (Hernich, Konev, and Wolter) has been supported by EPSRC projects *iTract: Islands of Tractability in Ontology-Based Data Access* and *quantMD: Ontology-Based Management of Many-Dimensional Quantitative Data* (total £930k). Outputs from these projects have influenced research in both knowledge representation (AIJ'16) and databases (TODS'14).

Our research in game theory applies to control, verification, and economics. In optimal control and program verification, the research of Fearnley and Schewe has been funded by the EPSRC projects *Energy Efficient Control* and *Solving Parity Games in Theory and Practice* (total £1M). Within economics, our research on equilibria and mechanism design (Christodoulou, Fearnley, Krysta, Savani) has been supported by EPSRC projects *Efficient Algorithms for Mechanism Design Without Monetary Transfer*, *Algorithms for Finding Approximate Nash Equilibria*, *Worst-Case Guarantees in Auction Design*, and a European Space Agency project on game-theoretic analysis of space debris removal (total £936k). These projects led to a large number of high-quality outputs (e.g., STOC'15, SODA'16).

RS2 (Interdisciplinarity):
As discussed in Section 1, our co-leadership with Chemistry of the Leverhulme Research Centre for Functional Materials Design (CFMD, £10M funding) has been one of our main strategic initiatives in interdisciplinary applications of computational methods. This initiative, which only started in 2017, has already proved very successful. For example, Kurlin and an interdisciplinary team have used machine learning to discover two novel co-crystals (Chemistry Science, 2020). Kurlin's work is also supported by the EPSRC project *Application driven Topological Data Analysis* (£3.5M, UoA £700k).

Our involvement in three EPSRC Hubs for robotics in hazardous environments illustrates our collaborative approach with other universities and commercial partners. Using the interdisciplinary Centre for Autonomous Systems Technology (CAST) as a platform, the UoA was involved in the *RAIN Hub* (Robotics and Artificial Intelligence for Nuclear), the *ORCA Hub* (Offshore Energy Asset

Integrity Management), and the *FAIR-SPACE Hub* (Future AI and Robotics Hub for Space), with a total volume of £34M (UoA £2.8M). Another large-scale collaboration is the EU Gamma project on Autonomous Mission Management Applications in which the UoA is jointly involved with the Virtual Engineering Centre using our expertise in verification (total £9.1M).

In a collaboration with medicine, the UoA was part of the EU WEB-RADR project (EUR 5.9M) to study adverse drug reactions, where the UoA provided the main expertise in the analysis of social media data. Another example where the unit has worked on data analytics for health is the MRC project "Supporting Evidence-based Public Health Interventions using Text Mining", joint with University of Manchester (Goulermas, UoA £330k).

RS3 (Targeted Impact):

To promote collaboration with industry and other non-academic partners, the UoA has targeted KTPs. This has led to ten KTP projects with an overall volume of £2.4M over the REF period. A typical example illustrating the technological and economic impact of these collaborations is provided by a KTP with Riverview Law, a Merseyside-based alternative legal services provider. Using research by Atkinson and Bollegala in natural language processing, the KTP produced software that reduced the processing time of legal documents in crucial data migration tasks by 350%. This very significant progress contributed to the successful deployment of Riverview Law's virtual assistants and, ultimately, the acquisition of Riverview Law by Ernst and Young in 2018. Other examples include further KTPs in the legal domain, with a blockchain software company, and with online retailers. Two KTPs with CSols Ltd, a company that produces software for laboratories, underpin one of the unit's impact case studies.

Besides KTP projects, during the REF period the unit undertook 20 direct industry projects that similarly focused on knowledge exchange. For example, Savani built on his research in reinforcement learning to help Stratagem Technologies (now a part of Blockchain.com) apply this technology for automated trading in sports betting markets; Luo (ECR), an expert in robotics and tactile sensors, helped Magellan Robotech Ltd to develop a prototype of a robotic shop agent; Goulermas used his expertise in machine learning and data analytics to help Kromek Ltd build an isotope identification system; Zamaraev (ECR) helped InsoftGlobal Ltd to explore new knowledge graph representations for the users of their cloud computing services.

3.2 Research Infrastructure

To accommodate the growth in faculty, we have created 5 new offices within the main unit building. Our strategic research infrastructure investments during this REF period primarily support RS2 (*Interdisciplinarity*) and RS3 (*Targeted Impact*). These investments, described below, can all be seen within their wider context in Figure 1.

AI Research Labs.

Very early in the REF period and as part of its investment in the AI cluster and the interdisciplinary Centre for Autonomous Systems Technology (CAST), the UoA decided to invest in two AI research labs, the smARTLab and the Home Robots Lab. Later in the REF period, and in collaboration with Geography, a third lab focusing on geographic data science combined with AI methodologies was added to our portfolio of lab support for AI research.

- **smARTLab.** The smARTLab is a state-of-the-art robotics laboratory that includes two large experimentation facilities, one for drones and one for ground-based robots. The lab hosts £300K of specialist facilities including: a collaborative (UR5) robot arm, two state-of-the-art robot grippers, a wide variety of drones and robots, including KUKA youBots, and a motion capture system. The smARTLab currently hosts 9 PhD students. Achievements include winning the 2014 RoboCup@work and RoCKIn2015competitions. The smARTLab team played a major part in developing the Sprung a Leak installation at Tate Liverpool, a key component of one of our returned impact cases.
- **The Home Robots Lab.** This lab emulates the internals of a house, in which robots are deployed and developed for domestic/social care. The lab comprises several Pepper, NAO, and Miro robots, all within a Vicon tracked space. The lab plays a key role in the above-mentioned EPSRC-funded projects *Trustworthy Robotic Systems* and *Verifiable*

Autonomy. The lab also enabled the robotics outreach activities in the North West that is part of one of our returned impact cases.

- **The Geographic Data Science Lab (GDSL).** The GDSL was founded in 2015 to host interdisciplinary work at the intersection between Data Science and Geography, applying machine learning to spatial data to inform decision making. The primary leads of GDSL are Singleton and Arribas-Bel, who are based in Geography, with honorary positions in Computer Science. Atkinson, Kurlin and Savani are involved in the areas of AI and law, topological data analysis, and generative modelling. The GDSL enabled our impact case study "Geographic Data Science". The case includes public sector impact via the GDSL's "Transport Classification of Londoners", which is now fully embedded in planning application processes in London.

Interdisciplinary Centres and User Collaboration.

The UoA is a key user of recent investments of the University of Liverpool in facilities for interdisciplinary research and collaboration with non-academic partners.

- The **Materials Innovation Factory (MIF)** is a £81M investment of the University of Liverpool and Unilever as part of the UK Research Partnership Investment Fund (UKRPIF). Its aim is to accelerate materials discovery through the use of robotics and high-performance computing. Together with the Leverhulme CFMD the infrastructure provided by the MIF is crucial for our strategic collaboration with Chemistry in Computational Materials Design and Intelligent Automation, as discussed earlier. Together the CFMD and MIF support a large number of PDRAs and PhD students that are jointly supervised between Chemistry and the UoA. A notable example of success is PhD student Burger's work "Automation: Chemistry shoots for the Moon" (Nature Technology Feature).
- **Sensor City** is a £15M joint venture between Liverpool John Moores University and The University of Liverpool that brings together academics and commercial partners developing sensor technologies. As two example projects, Savani is working with Engineering and Medicine and SME Foot-ZZ to develop AI-driven wearable sensors for monitoring sleep position; Gairing has a project with General Data Protected Ltd to showcase the use of secure sensors.

These centres were founded in 2018 and 2017 respectively, so they are strategic investments for the future development of the UoA and new research outcomes and impacts are only just emerging. Looking further to the future, the unit has been instrumental in establishing the new $1{,}530m^2$ **Digital Innovation Facility (DIF)**, which brings together complementary areas of research in Computer Science, Robotics, and Engineering. The DIF is forecast to boost the city region economy by creating approximately 400 jobs. It will enable a step change in our engagement with users in the areas of AI and Robotics, with CAST, the smARTLab, and the Home Robots Lab moving into the DIF in 2021.

Computing infrastructure.

All members of the unit have access to high-performance workstations (Intel Xeon), along with 15 GPU servers for shared use. At the university level, there are two main HPC clusters. The newest and most powerful is the Barkla HPC system comprising 105 nodes, each with 40 cores and 384GB of memory (two nodes have 1.1TB of memory). All these facilities are heavily used by the unit, in particular for deep learning (by the smARTLab) and in automated reasoning (by the Logic cluster). A notable example is the computational proof of a special case of the Erdős Discrepancy Theorem by Konev and Lisitsa (AIJ'15). Our shared facilities use job-scheduling systems that ensure fairness across all user groups, including ECRs, PDRAs, and PhD students.

The Virtual Engineering Centre provides the unit with access to STFC's Hartree Centre, a £170M government-funded HPC centre. To illustrate, the Economics cluster used this facility in the European Space Agency project on space debris, mentioned earlier. The Hartree Centre is also a key partner on the EPSRC CDT on Distributed Algorithms.

Going forward, we will also use the recently established GPU-focused Bede Facility of the N8 Centre of Excellence in Computationally Intensive Research (N8 CIR).

3.3 Plans for funding and infrastructure

With our large number of ECRs, a key priority for the next REF period is to effectively support our new faculty to win external research funding. A second priority is to leverage the MIF, Sensor City, and the DIF for new funding applications and projects with non-academic partners. The DIF, in particular, which is due to open in 2021, offers a major opportunity for new interdisciplinary collaboration and interaction with research users in the areas highlighted for strategic growth in Section 1. Our final priority relates to funding for our impact activities. We aim to complement KTPs with applications to other Innovate UK schemes, such as "demonstrator" projects.

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

Our vision of being a world-leading department in our core research areas and applying our research to the benefit of the economy and society can only be realised through national and international collaboration with world-leading computer scientists, other disciplines, and with potential users of our research. Our strategy for collaboration is based on RS1 to RS5.

4.1 Research Collaborations within the Discipline

Our collaborations within the discipline are guided by RS1 *Core Strengths*. Our main mechanisms to foster and support new and existing collaborations are:

> **P1**: Invite excellent computer scientists to Liverpool to collaborate with us and inspire our young researchers, from PhDs, to PDRAs, and ECRs.
>
> **P2**: Encourage collaboration with other researchers, nationally and internationally through travel funding and support for research projects.

In line with P1, the unit runs a weekly seminar with 168 invited speakers over the REF period. Invitees are typically funded to stay for two or more days and often give additional technical talks at research group level and to PDRAs and PhDs. Invitees are determined 'bottom up' from the research groups. The unit also provides funding for visiting fellowships (38 over the REF period), where researchers obtain funding to stay for at least a week. Around 50% of the fellows were hosted by faculty that were ECRs at the time of the visit. The fellowships have contributed to strong outputs and project proposals, for example, a Marie Skłodowska Curie Fellowship for Hahn (held at Liverpool) and papers at conferences such as CAV, ICALP, and IJCAI.

We are an international department and collaboration is fundamental to our approach. As an illustration, 20 out of our 28 ICALP papers during this REF period have a co-author based outside the UK; for Algorithmica, AAAI, and IJCAI, the numbers are 17/28, 21/27, and 35/41, respectively. In line with P2, the unit supports travel to visit research collaborators and conferences (£210K internal funding over the period), through sabbaticals (8 over the period), and support for joint research projects through PhD studentships and reduced teaching loads.

More than three quarters of our externally-funded research projects are joint with researchers from other institutions. For example, in addition to being a member of a number of large-scale EU projects, and a founding member of the EPSRC networks on Algorithms and Autonomous Systems, the unit has joint research council projects with Birkbeck, Durham, Edinburgh, Glasgow, Oxford, Sheffield, Swansea, and Warwick. These multi-site projects, and their associated research visits and seminars, contribute to the unit's rich and vibrant research environment, not only for faculty, but also for PhD students and PDRAs.

4.2 Engagement and Contributions beyond Academia

In line with RS3 *Targeted Impact*, the UoA engages with a diverse set of non-academic partners across many contexts. In this way, the unit is exposed to a wide range of research challenges that are based on real-world problems. We next highlight some of our most noteworthy engagements with non-academic users.

Engaging with the public.
In line with RS3.2, the unit believes that it is important to explain to the public our research and its relevance to society. To this end, the UoA has played a very significant role in the University of Liverpool's partnership with the Tate Art Galleries. For example, the UoA co-created with artist Cecile Evans the Sprung a Leak installation at Tate Liverpool, which explored the interaction between humans and AI and thus raised awareness and contributed to this important public debate. The installation plays a central part in one of the UoA's impact cases, and was a key reason behind Liverpool winning the "Partnership of the Year" PraxisUnico RCUK Impact Award, 2017.

In addition, during this REF period the unit has regularly interacted with the public via both local (for example, BBC Radio Merseyside and the Liverpool Echo), and national media (for example, Tomorrow's World Live, BBC; Granada Reports, ITN News; Today Programme, BBC Radio 4; Law in Action, BBC Radio 4; The Times and Sunday Times). Particular topics covered include AI and the legal sector, autonomous systems, the future of AI, and robotics (Atkinson, Collins, Dennis). We also engaged with the public through academic events including the LivWise Festival 2018 (Liverpool Women in Science & Engineering) and the Royal Society AI Roundtable 2019.

Engaging with the private sector.
In line with RS3.1 and as discussed in Section 3.1, the unit interacts with the private sector via KTPs, consultancy, the MIF and Sensor City, externally-funded research projects, and industry-focused Centres for Doctoral Training. Here we expand on the discussion in Section 3.1 about our industry engagement in the area of AI and Law. In addition to the collaboration with Riverview Law, in a KTP project with Fletchers Solicitors, Atkinson, Bollegala, and Coenen developed automated decision support tools for processing medical claims. The tools have affected several parts of Fletchers' operations, yielding dramatic time savings, improved reliability, and better decisions. Fletchers estimate that these new tools have transformed the working practices of 350 of their legal staff. In a third project, a consultancy with national law firm Weightmans, the unit applied its methodology for factor-based reasoning in legal cases to several of Weightmans' domains. The outcomes of this project were recognised by the prize for 'Best use of technology' at the 2019 Modern Law Awards.

Ethics in AI and International standards.
During this REF period, the unit has played a key role in the development of new international standards for robotics, ethics, and autonomous systems. Underpinned by their research in the verification and ethics of autonomous systems, Dennis, Dixon and Fisher have contributed to the IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems; Dennis is serving on the IEEE P7001 committee, "Transparency of Autonomous Systems", Fisher is serving on IEEE P7009, "Standard for Fail-Safe Design of Autonomous Systems", and Dixon and Fisher have served on the British Standard Institute AMT/10 committee on Robotics. Fisher contributed to the 2018 International Red Cross report "Autonomy, artificial intelligence and robotics: Technical aspects of human control". More recently, supported by two Dstl-funded projects, Huang and Schewe have continued this engagement by studying coverage metrics for artificial intelligence. This work features in the SCSC-153 document of the Safety of Autonomous Systems Working Group.

Democracy.
Good voting methods are needed for democracy to work well. The unit (Laraki) has pioneered a new voting method know as *majority judgement* (MJ). Its key feature is that it allows grading of options rather than picking winners. This allows fairer and in particular more representative outcomes. During this REF period, Laraki has conducted large-scale field experiments to test MJ. The experiments included the presidential election in France. By now, MJ is used in many contexts. For example, the British Academy uses MJ to elect its members, and, in 2020, several municipal elections in France ranked candidates using MJ.

Health and Wellbeing.
The unit has a long tradition of collaborating with the health and social care sectors. To illustrate, Jimmieson has been co-developing the In My Shoes tool with Child and Family Training from 1991 until the present. In My Shoes is a unique software tool used in social care and related contexts for interviewing children and vulnerable adults. It was returned as an impact case in REF 2014.

Since then, three new apps have been developed and a further 260 practitioners have been trained in using the tool in their day-to-day work. As another example, Payne has been collaborating with Rowe, Professor in Orthoptics in Liverpool. They have produced a visual impairment screening assessment tool (VISA) for acute stroke survivors, which is a crucial part of a REF 2021 impact case in UoA4 Neuroscience. Our recently established PhD network in AI for Future Digital Health has initiated collaborations with partners ranging from Alder Hey Children's Hospital to Public Health England.

4.3 Leadership, Interdisciplinarity, and Responsiveness

We aspire to use our research expertise to advance computing and its role in interdisciplinary research. To that end, we lead international research organisations: Atkinson served as President of the International Association for Artificial Intelligence and Law, Spirakis as President of the European Association for Theoretical Computer Science (EATCS), and Wolter as President of Knowledge Representation (KR) Inc. We also serve on important national committees and panels: the Lord Chief Justice's advisory group on AI (Atkinson), the LawtechUK Panel established by the Secretary of State for Justice (Atkinson), the London Mathematical Society Computer Science Committee (Wong, Committee Chair), the EPSRC Strategic Advisory Team (Fisher and Wong), and the REF 2021 panel (Atkinson).

Interdisciplinarity is at the core of our strategy (RS2 *Interdisciplinarity*). At unit level, we have, for example, the core interdisciplinary Economics and Computation cluster that comprises 10 faculty. At university level, we co-lead major interdisciplinary initiatives with Chemistry, Electrical Engineering, and Geography, as discussed in detail in earlier sections. Beyond the university, we have, for example, contributed to three EPSRC robotics hubs, worked with mathematicians at Oxford and Swansea on the large EPSRC project "Application Driven Topological Data Analysis", and collaborated with the European Space Agency.

4.4 Indicators of Wider Influence on the Discipline

Editorships. Spirakis is an editor in chief of Theoretical Computer Science (TCS) and Wiebe Van der Hoek of Synthese. Overall, members of the department have served on editorial boards of 37 journals, including Algorithmica (Spirakis), Artificial Intelligence (Dunne, Van der Hoek), IEEE Transactions on Neural Networks and Learning Systems (Goulermas), International Journal of Game Theory (Laraki, Savani), Journal of Web Semantics (Payne, Tamma), Theoretical Computer Science (Gasieniec, Krysta), Transactions of the Association for Computational Linguistics (Bollegala).

Grant Panels. Spirakis served as chair of the ERC Advanced Grants Panel for CS in 2017, Payne as chair of consensus meetings for the European Horizon 2020 programme, and Atkinson as chair of a Research Council Panel in Finland. Panel memberships include: EPSRC panels (Goulermas, Wong, Fisher), Royal Society Newton Panel (Gasieniec), Foundations for Polish Science Panel (Gasieniec), Flemish Research Council (Van der Hoek), DFG panels (Wolter).

Chairing of Conferences and Programme Committees. Members of the department have been conference or programme chairs of 46 international conferences, including CONCUR (Schewe), FCT (Gasieniec), ICAIL (Atkinson), KR (Wolter), MFCS (Potapov and Spirakis), PODC and SSS (Spirakis), Reachability Problems (Potapov), SAGT (Gairing and Savani), Semantic Web Conference (Tamma), WINE (Christodoulou). Members of the department served on over 350 conference or workshop programme committees.

Organisation of Conferences in Liverpool. In the REF period, the UoA has organised the following conferences: DLT 2015, SAGT 2016, MFCS 2018.

Awards. Fellow of the EATCS (Spirakis, 2014), GI Dissertation Award for Best CS Dissertation in Germany, Austria, and Switzerland (Wild, 2016), Best use of technology prize at Modern Law Awards (Atkinson 2019), Best paper awards include: FEM 2018 (Dixon, Hustadt, Fisher); ICALP 2018 (Kowalski); IJCAI 2018 (Wolter); IWOCA 2018 (Zamaraev); PODS 2017 (Hernich and Wolter); SAGT 2016 (Ibsen-Jensen); SEFM 2016 (Schewe); Transactions of the Japanese Society for AI 2014/15 (Bollegala).

4.5 Future plans and strategy

Building on our international standing in Algorithms, Logic, Economics, and selected areas of strength in AI, we plan to be pro-active in setting the national research agenda in these areas, in particular in Automated Markets, verifiable AI, and AI and Law (as discussed Section 1). We will support our ECRs (only 3/14 got a UK PhD) to become active members of the UK research community by engaging with UK professional bodies and research councils, non-academic partners, and our interdisciplinary initiatives.