Institution: University of Leicester

Unit of Assessment: UoA11 Computer Science and Informatics

1. Unit context and structure, research and impact strategy

UNIT CONTEXT AND STRUCTURE

The University of Leicester's School of Informatics is internationally recognised for its excellence across a wide range of fundamental and applied informatics. Our research and impact activities thrive through a collegial atmosphere among a team of outstanding research staff and students, cutting-edge interdisciplinarity research, and a collaborative approach to seeking solutions to major societal and industrial challenges.

Over the REF period, the UoA has maintained expertise in foundational areas of computer science, such as algorithms, formal methods, logic, and semantics. We have substantially strengthened areas of challenge-led research, including Artificial Intelligence (AI) and machine learning, algorithmics and formal methods, model-driven engineering, and validation and verification. Consequently, Leicester is now exceptionally well-placed to provide leadership addressing challenges relating to trust in autonomous and data-driven systems.

Headline achievements during the REF period include:

1. Major developments in foundational areas of computer science, including, controller synthesis and model checking (**Piterman**, **Ringert**), design and analysis of data structures and graph algorithms (**Raman**, **Erlebach**, and **Hoffmann**), and formal specification and formal verification of file systems and network protocols (**Ridge**).

2. Novel applications of informatics research in industry and healthcare, including machine learning for biomedical applications (**Zhou**), evolutionary algorithms with impact on autonomous planning systems in transport and service sectors (**Burke** and **Drake**), and validation and verification of autonomous and cyber-physical systems (**Mousavi**).

3. Significant research impact ranging from improvements to online STEM education worldwide (**Law**, ICS 1) to enhancing the performance and flight time of satellite systems (**Vladimirova**, ICS 2).

4. Improvements to our research and impact strategy following REF2014 also enabled more ambitious interdisciplinary projects. Recent successes include leading the £3M 'UK Verifiability Node' in the EPSRC Trustworthy Autonomous Systems programme (**Mousavi**), the £2M Personalised Space Technology Exercise Platform project (UK Space Agency, Ng), contribution to the development of Space Park Leicester, and the establishment of the new Centre for Artificial Intelligence, Data Analytics, and Modelling Centre.

The School's research is organised functionally into three Research Areas: (1) **Algorithms and Artificial Intelligence**; (2) **Interaction Design and Evaluation of Socio-Technical Systems**; and (3) **Modelling and Verification of Systems**. The Research Areas operate as

nuclei for research staff and students with related specialisms. Researchers work seamlessly across and beyond these areas, stimulating interdisciplinary interactions and developing strong collaborations across the health, space, and engineering sectors.

The unit's challenge-led research is now broadly focused around two cross-cutting interdisciplinary Research Themes: (1) **Trustworthy Autonomous Systems** (led by **Mousavi**), which integrates our in-depth expertise in AI, formal methods, human-computer interaction, machine learning, model-driven engineering, optimisation, and validation and verification to ensure autonomous systems can be built in a way society can trust and use; and (2) **Biomedical Informatics** (led by **Heckel**), which addresses challenging healthcare issues through data science, AI, machine learning, and image analysis.

RESEARCH AND IMPACT STRATEGY

Objective. Our overarching objective is to create a dynamic, scientifically-rigorous, and inclusive environment that supports our staff and research students to produce high-quality and impactful research. We aim to provide an environment that facilitates productive collaborations and interdisciplinarity, stimulating both curiosity-driven and challenge-led research with real-world benefits. While maintaining strengths in core computer science disciplines, we are quickly emerging as leaders in highly impactful research relating to trust in autonomous systems.

Key principles. The 7 guiding principles of our research and impact strategy are to:

1. Build on existing and emerging research strengths in trustworthy autonomous systems and biomedical informatics.
2. Support interdisciplinary collaborations tackling societal and industrial challenges.
3. Facilitate impact, innovation, and application through knowledge exchange activities and by working closely with industry.
4. Recruit, develop, and support outstanding academic staff and mentor early career researchers.
5. Attract and support high-quality research students and develop a community of well-rounded and highly employable researchers.
6. Increase the diversity and volume of our funding portfolio to support research and impact activities, and provide support for the preparation of large cross-disciplinary research proposals.
7. Increase engagement with our research by embedding an open research culture.

Approach to impact

There has been a significant increase in our outward-facing activities. Impact is now an inherent part of our research planning, with six KTPs established during this REF period compared to just one in REF2014. The principal beneficiaries of our research are the general public, students, teachers, and schools, international space agencies and the UK space industry, and health and engineering sectors. We have significantly grown industrial informatics, with a 14-fold increase in industrial-related income (£198k).

In REF2014, we outlined our aim to establish three pipelines to impact:

1. *To identify and develop high-quality research with potential for impact*.

We have appointed an Impact Coordinator (**Heckel**) and recruited **Burke** and **Anjum** to provide impact leadership. They support colleagues with identifying and developing impact pathways and communicate departmental capability to potential non-academic stakeholders. At institutional level, we benefit greatly from the expertise and support provided by the University's Research Impact Team and have been awarded £40k of internal funding specifically to pump-prime enterprising and impactful research.

2. *To develop and strengthen engagement with industry and key users*.
By collaborating with industrial beneficiaries, we have been able to identify major challenges faced by users of our research. The UoA has provided novel architecture for computing systems on board spacecraft, offering highly reliable operation and high-performance data processing capability. This led to significant economic benefit for international space agencies and industries, such as Airbus, as the flight time of their space systems increased greatly (**Vladimirova**, ICS 2). Participatory approaches to understanding user needs has also been key to delivering impact. Our commitment to long-term end-user engagement led to the successful translation of end-user preferences into technical and practical recommendations for developers of international online educational resources (**Law**, ICS 1). Over the REF period, our consultancy and contract research income totalled ~£226k, approximately double REF2014.

3. *To develop a collaborative interdisciplinary approach to real-world challenges*.
We believe that social and economic impact benefits from a multidisciplinary approach. We encourage our staff to build strategic partnerships with academics beyond computer science through key research networks and institutional infrastructure, such as the Leicester Institute for Advanced Studies (Institutional Environment Statement, section 2.2). Our engagement with the Leicester Precision Medicine Institute led to a significant role in the development of a new mobile application, Personalised Space Technology Exercise Platform (P-STEP, £2M, UK Space Agency). P-STEP will use space data and AI to deliver personalised exercise advice with pollution warnings, to assist patients with health conditions such as heart disease, COPD, and asthma (**Law** and **Boronat**). Another collaboration bringing together expertise in AI, robotics, human-computer interaction, systems and software engineering with colleagues from Leeds, Manchester, Sheffield, and York around the theme of trustworthy autonomous systems resulted in £3M to lead the 'UK Verifiability Node' on the EPSRC 'Trustworthy Autonomous Systems' programme (**Mousavi**, PI).

Achievements since REF2014

In REF2014, our two core strategic aims were to:

1) Grow and develop expertise in data mining and machine learning.
2) Grow and develop expertise in cyber security and trust.

During the REF period, we have successfully revised and revitalised our research and impact strategy to achieve these aims and enable researchers to undertake research of the highest quality, relevance, and impact. Through strategic hiring of four Chairs in areas related to AAAI (**Zhou**, **Anjum**), security (**Liu**), and trust (**Mousavi**), as well as two ECRs (**Rojas**, **Ringert**), the UoA has been able to develop expertise in data mining, machine learning, and verification and validation.

The following are brief descriptions of the three Research Areas (including participating Category A staff and those who have made a significant contribution to research) and selected research and impact highlights, as evidence of our unit's success within the REF period.

Algorithms and Artificial Intelligence (**AAAI**, led by **Zhou,** with **Anjum, Burke, Drake, Erlebach, Hoffmann, Liu, Raman**, and **Vladimirova**). This area is focussed on methods for large-scale and intelligent data processing. It encompasses sub-topics on intelligent data analysis; efficient, fault-tolerant, and distributed data storage and processing; and algorithms for complex optimisation problems on (uncertain) data. Our foundational research develops algorithms with provable performance and approximation guarantees; efficient and resilient distributed data infrastructures; new algorithms for image processing and understanding; and novel optimization techniques for NP-hard problems. We apply our research to problem domains in transport, health, and security. Highlights include:

1. Broad industrial impact in a range of industries and sectors, including advancements in deep learning in cell line authorisation with AstraZeneca (**Zhou**) and collaboration with CERN on big data analytics for high-energy physics experimental data (**Anjum**).
2. Collaboration on the EPSRC 'OR-MASTER' project, developing mathematical models and algorithms for allocating scarce airport resources and addressing issues of airport congestion and capacity, in collaboration with 16 academic and air transport industry partners (**Drake** and **Burke**).
3. Leadership in research on succinct data structures (**Raman,** plenary talks at SPIRE 2015 and WALCOM 2015, and invited tutorial at ACM SIGMOD-PODS 2018).
4. Leading investigations into algorithms for computing with uncertainty (**Erlebach** and **Hoffmann**, EPSRC £401k), e.g., their application to develop a fleet of drones with enhanced search and rescue capabilities in the Brecon Beacons (**Hoffmann**) in collaboration with TrailMed, a medical service SME.
5. Co-founder, with five other UK institutions, of the EPSRC Network on Algorithms and Complexity (**Erlebach** and **Raman**).
6. Establishment of the Artificial Intelligence, Data Analytics and Modelling Centre (**Liu**).

Interaction Design and Evaluation of Socio-Technical Systems (**IDEAS**, led by **Law,** with **Boronat**, Heintz, Kefalidou**,** and **Liu**). IDEAS focuses on designing and evaluating interactive technologies with Human-Computer Interaction (HCI) methodologies in a range of application domains such as education, health, and transport. We have established and developed strong relationships with researchers working in mathematics, physics, engineering, medicine, psychology, law, business. Its overarching goal is to enhance people's quality of life through technology, as well as advancing key theoretical issues. Highlights include:

1. Pioneering research into the use of video games in education and usability and user experience methodologies has enhanced the learning experience for children worldwide (ICS 1, **Law**). Participatory Design research and implementation of PDot, an online tool, resulted in high-quality free online STEM educational resources, with 90,000 students and 31,000 teachers across 45 countries benefitting from the software (two EU projects: 'Go-Lab' £713k and 'Next-Lab' £290k, **Law** and Heintz).
2. Gathering empirical data with a country-wide survey in China to understand the prevailing IPR awareness of designers in Chinese creative IT industries and thereby capturing requirements to develop a prototype for a mobile app on retrieving patents (£82k, AHRC, **Law,** Int. J. HCI 2020).

3. Working on social and human-related aspects of healthcare and biomedical systems with colleagues in Life Sciences has led to several projects in human-centred approaches to healthcare systems and healthcare data-analytics, including the £2M P-STEP project (**Law** and **Boronat**).
4. Working on human-centric approaches to the design of autonomous and cyber-physical systems; for example, on human-centric approaches for event-driven architectures (**Lu**, *IEEE Transactions on Computational Social Systems* 2019)
5. A programme of public engagement activities regarding Trust in Autonomous Vehicles (Kefalidou).

Modelling and Verification of Systems (**MOVES**, led by **Mousavi,** with **Anjum**, **Boronat, Burke, Drake, Heckel, Piterman, Ridge, Ringert, Rojas, Tuosto, Türker, Ulidowski**, **Crole**, and **Vladimirova**). MOVES focuses on establishing trust in autonomous and data-driven systems. We build upon the foundations of systems modelling and develop automated software and systems engineering. We perform research on a range of validation and verification techniques, including formal verification and synthesis to search-based and model-based testing. Our main activities include using AI to develop efficient and effective verification of autonomous systems, as well as using rigorous techniques to establish quantitative verification results on AI-enabled systems. Highlights include:

1. Leadership in areas of validation and verification research, including an ERC Consolidator Grant for the 'Distributed Synthesis: from Single to Multiple Agents' project (~£1.3M), developing the theoretical foundations that enable reactive synthesis in the context of multiple agents (**Piterman**). The UoA was also recently awarded ~£3M (EPSRC) to spearhead work ensuring that autonomous systems, such as driverless cars, drones, and robots, are reliable and dependable (PI: **Mousavi**. Collaborators: Kefalidou, **Law**, **Ringert**, **Rojas**, and **Türker**).
2. Advancements in state-space analysis has had a major impact on systems biology (**Piterman**). **Piterman's** work has been incorporated into the Bio Model Analyzer tool, used to create and analyse executable models of protein interactions. The tool was used for models published in several important papers in *Nature Comms* 2018, *Cancer Research* 2017, and *Scientific Reports* 2017, on topics related to cancer research. Furthermore, **Piterman's** work on synthesis describes the technique used to analyse blood development in mice in a highly-cited paper in *Nature Biotechnology 2015* (FWCI 12.8).
3. Development of consistency in distributed systems for the fusion of clinical and genetic data in collaboration with Roche, a Swiss pharmaceutical company (**Anjum**).
4. Development of rigorous theory, tools, and implementations for consistent data stores, including SibylFS mechanized semantics for POSIX and real-world filesystems (**Ridge**), usable from theorem provers such as HOL and Isabelle/HOL, and simultaneously functioning as a real-world filesystem testing tool.
5. Academic leadership in national and international research initiatives, including leading the EU COST Action 1405 on 'Reversible Computation' (422K, **Ulidowski**), organising Reversible Computation 2018 Conference at Leicester (**Ulidowski**), and founding and directing the Midlands Graduate School on Foundations of Computer Science (**Crole**).
6. Marie-Curie Fellowship grant on reversible computation (£131k, **Ulidowski** and **Tuosto**) and a Marie-Curie mobility grant on concurrency theory (BehAPI, £77k, **Tuosto**).
7. Setting the international agenda for hyper-heuristics, motivated by the goal of underpinning the development of computational methodologies that can automatically build decision support systems (**Burke**: *International Series in Operations Research and*

Management 2019, FWCI 30.61; *European Journal of Operational Research* 2017, FWCI 6.6)

Governance and integrity. The School's Research Committee are responsible for reviewing our research and impact strategy. This comprises the Research Area and Theme leaders, the Head of School, Director of Research, and representatives from early- and mid-career researchers. The Committee is responsible for promoting a culture of research integrity and we expect all researchers to embed best practice in all aspects of their work. We adhere to institutional requirements (IES, 2.7) and ensure all researchers understand the expected standards of integrity, as outlined in the Concordat to Support Research Integrity. The Committee is also involved in other strategic decision making, such as allocation of support, travel funds, and other resources for enabling research and impact.

Open research. In addition to adhering to REF requirements and institutional policy (IES, 2.6), we are increasing the open accessibility of our research. In Leicester's first Open Research Survey (2020), 83% of informatics researchers agreed that their understanding and awareness of open research had improved since 2014 and that they had made more of their research freely available and accessible. Many of our researchers are editors and/or on the editorial board of open-access peer-reviewed journals, including *MDPI Computers* (**Heckel**) and *Electronic Proceedings in Theoretical Computer Science* (**Ulidowski**). We regularly share preprints, tools, data, methods, and code via open platforms such as *Gitlab*, *Github*, and *arXiv*.

Future Research Plans

To support our objective of becoming international leaders in trust in autonomous systems, we plan to expand our expertise in: (1) data-driven and AI systems; (2) software and systems engineering for autonomous systems; and (3) social aspects of computing and human-computer interaction. We will foster interdisciplinary collaborations, particularly with the School of Mathematics, where we see excellent collaboration opportunities in AI, risk analysis, and simulation and real-time diagnosis of autonomous systems.

We are also playing a significant role in the development of Space Park Leicester (IES, 2.1, 4.1). Utilising our expertise in data science, AI, software engineering, validation and verification, researchers from this UoA will lead one of the main work packages for the Manufacturing, Engineering, Technology and Earth Observation Research Centre project. METEOR will be a key part of SPL, bringing together academic research and industrial space and Earth observation R&D. The centre represents an internationally unique approach to understanding and delivering space capabilities, revolutionising how satellites are conceived, designed, operated and produced, as well as how data derived from them is interpreted and used to solve real world problems.

2. People

STAFFING STRATEGY AND STAFF DEVELOPMENT

Staffing strategy. Our overarching goal is to recruit and retain exceptional computer scientists to deliver research excellence across our Research Areas. To achieve this, we have developed the following strategy:

1. We recruit outstanding staff at all career stages to enhance research and impact.
2. We target appointments that are in line with our cross-cutting interdisciplinary themes, as well as appointments that will facilitate and strengthen links with industry.
3. We retain staff by providing robust support and career development opportunities and recognise and reward success.
4. We ensure staff can flourish in an equal and inclusive working environment.

Staff recruitment and composition. All recruitment is conducted in a fair, transparent, and flexible way in order to attract a diverse pool of candidates. Appointments are made entirely on merit and assessed by diverse selection panels adhering to DORA-compliant principles. We value breadth and specialisation across a range of activities. On REF census date, the unit comprised 19.7 FTE of Category A Staff: 7 FTE Lecturers (including 3 ECRs), 3.5 FTE Associate Professors and Senior Lecturers, and 9.2 FTE Professors. Our research activity is further supported by 10.5 FTE of teaching-focussed members and 12 PDRAs and Graduate Teaching Assistants.

During the REF period, we have recruited staff to strengthen expertise and capabilities across our Research Areas and Themes. We have invested significantly in Verification and Validation research (**Mousavi**, Chair; **Ringert, Rojas,** and **Türker**, Lecturers). New appointments were also made in Combinatorial Optimisation and Evolutionary Algorithms (**Burke**, Chair), AI and Data Analytics (**Anjum**, Chair), Security and Big Data Analytics (**Liu**, Chair), AI and Image Processing (**Zhou**, Associate Professor), and Optimisation and Evolutionary Algorithms (**Drake**, Lecturer).

Staff development and promotion. We ensure that the principles of the Concordat to Support the Development of Researchers are implemented at School level. All staff have an annual Performance Development Discussion (PDD) with the Head of School. Evaluating research and impact performance and identifying training needs are core components of these discussions. PDD reports are reviewed by the Head of School to identify candidates for promotion and consider whether interventions are required, e.g., workload adjustments and additional mentoring.

We have an active and fully-paid study leave programme. Typically, staff can take leave to focus on research and impact for one semester in every seven. There are rigorous application and evaluation procedures for study leave involving the Research Committee, with subsequent review and approval by the College to ensure that staff achieve maximal benefit and that study leave goals are ambitious and deliverable.

All academic staff have access to a dedicated School research and travel fund to support a range of activities that support the development of research and impact. This is done by redirecting a fraction of grant overheads and QR funds to individual researchers. Under this scheme, 22 staff have been granted travel funds and 11 were awarded funds to complete follow-up activities. For example, **Erlebach's** travel fund in 2018 resulted in a collaborative journal article introducing a novel adversarial model for scheduling with explorable uncertainty (*Algorithmica* 2020) and a subsequent EPSRC grant (£400k) investigating algorithms for computing with uncertainty.

Staff across all Research Areas regularly take part in research seminars, providing an opportunity to present research, promote best practice, and facilitate collaborations. In addition, the UoA facilitates exchanges between staff and non-academic stakeholders through

the Leicester Innovation Hub (IES, 2.5), by leading and participating in LIH events that demonstrate our expertise and potential to provide innovative product solutions to industrial partners.

We encourage all staff to utilise training provided by the Doctoral College (IES, 3.2). **Law** and **Mousavi** took part in the Leicester Future Leaders' Programme, which aims to foster a community of diverse leadership talent. For promotion cases, knowledge exchange, enterprise, and impact, as well as research, are key parts of the assessment criteria. During the REF period, **Law** and **Zhou** were promoted to Professor and **Ridge** was promoted to Associate Professor.

Early Career Researchers (ECRs). All ECRs receive reduced teaching loads and are offered flexible start-up packages to accelerate progress. ECRs are assigned a mentor with whom they meet regularly to discuss research and impact goals. The School further operates a 'buddy' scheme, wherein ECRs are paired to facilitate peer support, peer learning, and cultivate a productive, collegial, and inclusive research culture. The scheme's value has also been acknowledged through our Athena SWAN Bronze award renewal (2018).

The School has enrolled ECRs to the University's EPSRC New Investigator Grant Cohorts scheme. All are currently taking part in EPSRC First Grant training and their bids are in preparation. The scheme provides training workshops specifically for ECRs to support them in formulating and submitting a bid that, if successful, will underpin a self-directed research project. **Piterman** and Minku have attended this training and were successful with their bids, respectively, for an ERC Consolidator Award and an EPSRC First Grant.

ECRs who have been supported through these mechanisms have been successful in securing funding for independent research activities, including: An Independent Fellowship (Chitchyan); an EPSRC First Grant (Minku); an EPSRC and an ERC Consolidator grant (**Piterman**, total ~£328k); an MRCUK grant (Verdezoto); and a Health Foundation grant (Kefalidou). All have gone on to secure more senior academic positions.

Visiting Scholars. To promote international collaboration, the School regularly hosts visiting scholars, for example: Mariangiola Dezani-Ciancaglini (Italy), Ed Fredkin (USA), Frank Kammer (Germany), Barbara König (Germany), Simon Puglisi (Helsinki), Zia Qayyum (Pakistan), Ivan Lanese (Italy), Norman Margolus (USA), Hernan Melgratti (Argentina), Michael P Frank (USA), and Shoji Yuen (Japan). A number of these visits have been funded by academic councils and Governments and all have resulted in high-quality outputs, some including our PhD students.

RESEARCH STUDENTS

We highly value our research students and their contribution to the research environment. During the REF period, 58 research students completed their doctorates, representing a 39% increase since REF2014. The improvement in the size and success of our PhD community reflects both the quality of the research students we attract and a marked improvement in our research activity. In the 2019 Postgraduate Research Experience Survey (PRES2019), 94% of informatics PGRs who responded agreed that they were overall satisfied with the experience of their research degree programme.

Recruitment. Attracting both national and international research students through studentships, robust support mechanisms, and developmental opportunities is a strategic priority. Funding for studentships has come from an increasingly diverse range of sources, including EU funding, EPSRC, Microsoft, and British Telecom. PhD students are recruited via open competition and projects identified by staff are advertised on our web page each year. Applications are centrally administered and a panel interviews short-listed candidates. Successful applicants are selected primarily based on research potential, performance during interview, and academic experience. We also ensure new staff have access to PhD students as they begin to grow their teams.

Supervision. In PRES2019, 94% of our PGRs who responded agreed that their supervisor/s provide feedback that helps them to direct their research activities. Students meet with their supervisors on a weekly basis and these meetings are recorded by the student so that we can monitor engagement and attendance. Secondary supervisors are closely involved in the conception and development of the project. Progress is monitored more formally by a panel independent of the supervisory team at three and six months, and then annually until the viva. For the reviews, students are required to submit a written report detailing their progress and future research plans, as well as a training needs analysis form to inform a tailored training plan.

Training and development. In PRES2019, 94% of our PGRs who responded agreed that their 'skills in applying appropriate research methodologies, tools and techniques' had developed during their programme and 100% agreed that 'skills in critically analysing and evaluating findings and results' had developed.

Central training is provided by the Doctoral College. At local level, the School trains doctoral students in line with the Vitae Researcher Development Framework. For example, PGRs are required to attend the Graduate Seminar series, comprising short and intensive modules on research methodology, presentation and writing skills, and introductory material in areas of research. We also play an active role in the Midlands Graduate School, which offers specialised training in various areas of computer science.

We integrate PGRs into the academic community in several ways. PGRS are invited to present their research at the annual Informatics Postgraduate Research Day. PGRs are also given the opportunity to actively work with more senior colleagues, enabling practice-based peer learning. Research students have contributed to bids and collaborated with staff on exhibitions and events, e.g., the Royal Society Summer Science Exhibition and the DriverLeics initiative, a research and public engagement group relating to trustworthy autonomous systems. Our PGRs are encouraged to participate in external conferences and workshops and all have access to a travel fund. We also encourage participation in research competitions, such as the BCS Research Spotlight competition which led to an award for Cauli in 2017.

Employability and next destination. Since REF2014, our PGR graduates have progressed to a wide range of highly competitive academic and industry roles. Many graduates have gone on to secure academic positions, including: Research Associates (e.g. Oxford, Imperial College London, and Cambridge), as well as Lectureships in the UK (e.g., De Montfort and Wolverhampton) and overseas (e.g., China, Malaysia, Saudi Arabia, and Thailand). Others have gone on to secure industry positions, including roles in Software Engineering, Software

Development, Data Science, and Computer and Data Consultancy, at SMEs, Amazon, and Microsoft.

EQUALITY AND DIVERSITY (EDI)

EDI is a priority in the School. We adhere to the institutional EDI strategy and policies (IES, 3.1). We acknowledge that we cannot reach our full potential unless we can benefit from the talents of all and are committed to addressing issues of underrepresentation in our School.

Gender equality. Our work towards tackling gender inequality was recognised by an Athena Swan Bronze award (2013, 2018); however, we recognise there is still much work to do. On the REF census date, 8.7% of REF-eligible staff were female, 18.2% of Professors were female and nearly 30% of research students were female. We seek opportunities to increase the visibility of female staff and students and celebrate women in computer science. For instance, we invite female guest speakers from academia and industry to our events. We have organised successful outreach activities, including an 'Ada Lovelace' away-day for schoolgirls and the 'CodeFirst: Girls' course series for non-CS students. These activities aim to attract girls and younger women to informatics and ensure a more balanced gender profile for STEM subjects in the future. In 2015, we hosted our first Daphne Jackson Fellow (Severi).

BAME representation. We support cultural diversity, which is reflected in our international profile. On the REF census date, 26.1% of REF-eligible staff were BAME, 45.5% of Professorial staff were BAME, and 50% of our female staff identified as BAME. We also recently hired members of staff who were born in eight different countries (Bolivia, Bulgaria, China, Germany, Greece, Iran, Pakistan, and Turkey) and had their last appointments at six different countries (China, Israel, Sweden, Turkey, UK, and USA). Over the REF period, 48.1% of research students identified as BAME.

Monitoring and assessment. Feedback from the 2018 Athena Swan award panel agreed that the School had 'good consultation methods' for self-assessment, identifying issues, and creating action plans. EDI, including Athena Swan Self-Assessment Team (SAT) reports, is discussed in quarterly staff meetings and at Student Staff Committee meetings. EDI activities are communicated to staff and students via a dedicated virtual learning environment and learning management system. The SAT Chair is a University Equality Champion, meaning regular meetings take place to discuss EDI initiatives at a College level. We sustain close collaboration with the University Athena SWAN executive panel, the College Gender Equality Panel, and an Athena SWAN "buddy" department to exchange knowledge and best practice.

Inclusion. We ensure that meetings take place within our core hours to support staff with caring responsibilities. We also operate Flexible Working and Special Leave policies, and an Annual Leave Purchase scheme, to facilitate a healthy work/life balance and provide flexibility to staff in times of need. We have a wellbeing tutor to look after the health and wellbeing of our PGRs. To celebrate our achievements, we have several annual awards dedicated to recognising the contributions of our colleagues, e.g., **Law** was a finalist for the 2016 Discovering Excellence award and a nominee for the 2017 Research Impact Award.

EDI and REF. We are submitting all eligible staff in our REF return. UoL's REF Code of Practice specifies how our REF return has been compiled with due regard to EDI. In advance of this, we ensured a diverse mix of staff were involved in output quality review (38% of our panel were female). We have a supportive process in place for declaring staff individual

circumstances in relation to our REF submission, guided by our EDI Champion (Kefalidou) and University's EDI team. We have robust support structures in place so that even staff facing substantial challenges have been able to produce outputs for REF.

3. Income, infrastructure and facilities

RESEARCH INCOME

During the REF period, our research income totaled ~£3.8M, with a total spend per FTE of £196k—a 74% increase on REF2014 (£112k/FTE). Our principal sources of external research funding were awarded by EU governmental bodies (£2.4M), UK governmental bodies (£553k), EPSRC (£384k), and industry (£198k).

Strategy for generating research income. Following REF2014, the School committed to increasing its outward-facing activities, the success of which is reflected in a significant increase in both the volume and diversity of our funding portfolio. We have made notable gains in several areas, including a 1320% increase in industry funding, a 288% increase in funding from the UK government and health authorities, and a 107% increase in funding from EU government.

The School capitalises on College- and institutional-level support for the preparation and costing of research grant applications, provided by our Head of Department, Director of Research, Research and Enterprise Division, Research Institutes, and Key Funder Working Groups. Together, they raise awareness of funding opportunities and provide internal peer review of early-stage to fully-developed research proposals, mentoring, progress reviews, and workshops to ensure a good understanding of funder requirements. This support has enabled a sustainable upward income trajectory over the REF2021 period, from £423k in 2013/14 to £618k in 2019/20.

Increase in our research funding has enabled us to conduct innovative research and deliver considerable impact. Major grants include:

- A £2.5M European Regional Development Fund grant to underpin the launch of the Leicester Innovation Hub (Reiff-Marganiec). Based at UoL, the hub supports businesses through incubation, innovation support, and access to facilities, funding, and academic expertise. It has worked closely with over 100 companies to turn research and business ideas into innovative products, services, and processes.
- A £1.3M ERC Consolidator Grant for the 'D-SynMA' project, which has advanced distributed synthesis by considering novel interaction and communication concepts that have created an adaptable framework of correct-by-construction application of collaborating devices (**Piterman**, TACAS 2019).
- A £422k EU ICT COST Action grant on 'Reversible Computation' (**Ulidowski**). Working with over 150 scientists from 28 countries, it aimed to support the growth of foundations of reversible computation and apply the research outcomes in practical applications. Highlights include work on causal-consistent reversibility and its applications in reversible debugging tools, novel techniques for reversing Petri nets with applications in the modelling of biochemical reactions and wireless communication networks, design and

synthesis of reversible circuits, and applications of reversibility in programming industrial robots performing assembly operations.

Future funding strategy. We recognise that an over-reliance on a small number of sponsors creates vulnerability. Our strategy led to a more balanced research income profile with charities, industry, Government, and Research Councils, making our current and future research income streams more sustainable and robust to external economic and political fluctuations. We hope this diversity will provide a degree of insulation against changes in the funding landscape, supported by a strengthening of our industrial links and ensuring that we seize opportunities in areas relating to Trustworthy Autonomous Systems and Biomedical Informatics. With two large multidisciplinary grants already secured in these areas (£3M EPSRC, £2M UK Space Agency), we are ensuring that UoL continues to conduct innovative and impactful computer science research over the coming years.

INFRASTRUCTURE AND FACILITIES

Informatics researchers are based in the Informatics Building, which includes accessible offices, research and seminar space, and laboratories. The University further invested in a new modern building dedicated to Computer Laboratories for education and research. Construction was completed in 2020, ready for use post-lockdown.

Specialist laboratories and equipment. During the REF period, the University has invested £50k to host our Human Computer Interaction (HCI) Laboratory, equipped with Virtual Reality (VR) technologies. The HCI lab has supported projects such as the EU H2020 ARETE (£293k). **Law** and **Heintz** have made considerable advancements in understanding how specific design features of augmented reality can cultivate fruitful learning environments for school children, from improvements in literacy and STEM to positive behaviour. They have become leaders in successfully applying human-centred design in technology-enhanced learning by providing innovative Augmented Reality resources in the education system (*Int. J. H-C Studies* 2020).

The University has also been provided space to support our Artificial Intelligence Lab, as well as investment in a variety of specialist equipment, including high-specification computers, Vector robots, autonomous vehicles, and simulators. These led to successful public engagement activities (such as the Royal Society Summer Science Exhibition) and also in student and research projects.

High Performance Computing (HPC). UoL is renowned for its provision of nationally-significant HPC facilities (IES, 4.3). All staff and students in this UoA have access to two large HPC clusters, ALICE and SPECTRE, providing maximum performance for the most demanding data processing, data analysis, and simulation tasks. These facilities have been essential to support the development of our AI-based collaborations, including **Zhou's** collaboration with AstraZenecta (Cambridge), which aims to enhance the performance of recognising contaminated cell lines in cell images whilst minimising errors in identification and led to PhD funding.

Centre for Artificial Intelligence and Data Modelling (AIDAM). In collaboration with the School of Mathematics, we launched AIDAM in 2020. The centre carries out, consolidates, and integrates research on AI, data science, and machine learning to develop data-driven AI

systems that are resilient, robust, trustworthy, and adaptable to changing operational conditions. A major objective of AIDAM is to facilitate related fundamental and challenge-led research. In line with our two key interdisciplinary research themes—trustworthy autonomous systems and biomedical informatics—the centre supports, in particular, collaborations with Life Sciences and industry. Examples include the METEOR project with Space Park Leicester. In the short time since its launch, AIDAM has supported interdisciplinary projects and industrial partnerships totalling over £5.5M.

Leicester Institute for Advanced Studies (LIAS). LIAS facilitates new ways of modelling and translating interdisciplinary research (IES, 2.2). Our unit has secured and capitalised on LIAS-driven funding schemes designed to pump-prime interdisciplinary research networks, such as the Leicester Artificial Intelligence Network, and various interdisciplinary projects, including: the 'Digital Technology in Maternity Care' project, which has transformed the way we understand and harness digital technology in pregnancy, maternity care, and early parenthood in the UK, India, Peru, and South Africa (Verdezoto); the 'Leicester Ethnicity, Ageing and Dementia' project, which is developing clinical applications of AI and machine learning in healthcare (**Law**); and the 'Mental Health and Social Media' project, which explored the positive and negative impacts of social media on adolescents (**Law**).

Other institutional infrastructure. The unit has access to Leicester's award-winning library (IES, 4.1), including digital access to Computer Science libraries such as *IEEE* and *ACM DL*, *ScienceDirect*, and *Springer Link*. UoL provides comprehensive support for research, enterprise, impact, and knowledge exchange activities through the Research and Enterprise Division (RED). RED also provides support for the costing and preparation of research grant applications, including mock interviews, and keeps the School informed of new research initiatives.

Future investments. Within the next year, it is expected that the UoA will physically move into a newly refurbished building which will host both the School of Informatics and Mathematics, an investment worth ~£500k. This will enable a stronger and closer collaboration and joint research culture between these two departments, especially within the field and context of Trust in AI, Big Data Analytics, and Machine Learning.

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

During the REF2021 period, the School has facilitated and strengthened over 100 national and international partnerships. This includes collaborative projects with local, national, and international researchers, as well as industrial and governmental partners.

COLLABORATION WITH AND CONTRIBUTION TO THE RESEARCH BASE

We have been involved in several collaborative interdisciplinary projects. For example, **Law** (Co-I) collaborated with law scholars on 'Law in Children's Lives' (ESRC £20k). By engaging with end users, **Law** designed and evaluated the usability of a tablet-based game that aimed to explore how far children see law as an empowering force in their lives. The research led to six joint publications (e.g., **Law**, *Int. J. H. C. Studies* 2020) and feedback from the young participants was extremely positive: 'The game was AWESOME! And I learnt a lot!' (Girl, Year

5). LCL has opened new research opportunities to explore how 'gamification' can engage pupils and enhance education.

The UoA utilises its AI expertise to create new collaborative partnerships. With support from LIAS, members of AAAI formed the 'Leicester Artificial Intelligence Network', the University's first platform to promote interdisciplinary collaborations pivoting on AI. Consisting of 18 faculty from the Colleges of Life Science, Science and Engineering, and Social Sciences and Arts and Humanities, the network exists to bring together researchers working on all aspects of AI and drive innovative cross-disciplinary research agendas. LAIN has facilitated a variety of projects, including using AI for diagnosis in cardiac arrests and shoulder diseases and grants, including £3M from ESPRC to lead on the 'verifiability' aspect of autonomous systems (**Mousavi**).

Other examples include **Zhou** (Co-I) who, with academics from Criminology, Psychology, Mathematics, and Geography, is developing close working relationships with East Midlands police forces through the 'Violence Reduction Information Network', an ESRC IAA Strategic Partnership (£46k). VRIN aims to develop knowledge and share information concerning the prevention of public space violence, which will have a positive influence on policing operations in the region and beyond. **Zhou** is leading work on AI and face recognition to support the reduction of public space violence (*IEEE Tran. Image Proc.* 2020).

INDUSTRY COLLABORATIONS, BENEFICIARIES, AND PUBLIC ENGAGEMENT

Our work in applied informatics involves extensive engagement with industry partners and key users. Since REF2014, we have worked with more ~30 organisations across healthcare, space and earth observation, travel and transportation, education, and software and services companies to address major challenges. We have delivered significant economic and social impact, including developing high-performance analytics for medical systems; improving the performance of satellite systems; and reducing airport congestion.

Healthcare. We have initiated several strategic collaborations that will utilise, grow, and develop impact from our growing expertise in biomedical informatics, including AstraZeneca, TrailMed, and Roche. With Roche, for example, **Anjum** investigated a blockchain based distributed ledger infrastructure for trusted management of data coming from IoT devices in healthcare and developed a HyperLedger based infrastructure for an immutable and verifiable record of transactions between patients, investigators, and IoT devices.

Space and earth observation. We contribute to the University's international reputation as world leaders in space and earth observation research. Collaboration with Airbus Defence and Space and the European Space Agency led to significant economic impact by extending the flight time of satellites (ICS 2). **Vladimirova's** research helped to mitigate the effects of some of the harsh operating conditions in space that threaten the effectiveness of a satellite's flight time. By developing high-performance embedded computing systems and improving the reliability of satellite data processing systems, **Vladimirova** *et al* were able to extend the functional life of satellites, ensuring these flight times are more cost-effective and addressing gaps in knowledge in the space industry. Their research led to six outputs during the REF period, including articles in *ACM Computing Surveys Journal* (2015) and *IEEE Trans. Aerospace and Electronic Systems* (2016).

With Precise Crop Nutrition, **Vladimirova's** research further contributed to the development of a system to help farmers make better use of satellite images to develop variable rate nitrogen fertiliser application plans for their crops (Innovate UK/NERC, £45k to UoL) **Vladimirova's** expertise in satellites and high-performance computing helped Precise Crop Nutrition to offer a quicker and more flexible way to convert data and allow agronomists and farmers to be more closely involved in crop management recommendations.

Travel and transportation. We have partnered with national and international companies in travel and transportation, including Air France KLM, RollsRoyce, Zurich Airport. **Burke** is leading the 'Mathematical Models and Algorithms for Allocating Scarce Airport Resources' programme, with **Drake**, colleagues from the Universities of Stirling and Lancaster, and air transport industry organisations and policy makers. Tackling growing concerns over airport capacity, rising demand, and the impact of congestion, the six-year £2.8M (EPSRC) project is investigating—from a mathematical and computational perspective—whether capacity management is being realised as efficiently as possible, supporting policy makers and air transport decision makers in the UK and overseas to optimally allocate scarce airport resources (SSCI 2019). Furthermore, **Burke** and **Drake** are working together with Banedanmark to develop a constructive framework to tackle the problem of planning preventive maintenance of railway signals in the Danish railway system (*Journal of the Operational Research* 2019).

Software and Service. A strategic partnership with the Software Engineering Research Group at British Telecom led to three industrially-funded challenge-led PhD studentships. This includes, for example, a project on 'Automated Accessibility Testing for Mobile Applications', to develop a fully automated test generation approach to check the accessibility of mobile Android apps and evaluate the severity and relevance of the accessibility issues identified (supervised by **Rojas** and **Mousavi**). Additionally, **Drake's** and **Burke's** research into multiobjective evolutionary algorithms for strategic deployment of resources (*Journal of Operational Research* 2020), has allowed the planning team at BT to understand the unique complexities of maintenance problems they face in different areas of the UK, particularly with respect to the choice of number of operational units, and has strengthened their ability to design operational units effectively.

Public engagement and outreach. The School has a strong public engagement component on trust in autonomous systems. It includes activities at public fairs and festivals, such as the prestigious Royal Society Summer Exhibition and the Science Museum, and several outreach activities at open days and schools. The exhibition at the Royal Society Summer Science Exhibition 2019 had ~13,000 visitors, including over 2,000 school students. Our Late Event at the Science Museum attracted more than 4,000 visitors. We also produce educational material for the general public and maintain active web presence and communications for a lay audience. We gather data to evaluate public awareness and understanding and outreach. A preliminary report of this activity has been published as a paper co-authored by five staff members, two PGR, one graduate, and one undergraduate student (*DSCI* 2019).

ESTEEM AND LEADERSHIP

We have a strong base of faculty with prominent leadership roles in the community. We give select examples below.

Awards, recognitions, and fellowships	National/ international partnerships	Editorships	PC Memberships	Keynotes and invited talks
18 awards 4 fellowships 3 recognitions 1 patent	131 partnerships worldwide, including academia and industry	49 in different journals and venues	Membership of 287 international PCs	69 keynotes and invited talks

Table 1. Esteem indicators within the unit

Editorships. Examples include: Editor-in-chief of *Journal of Scheduling* (**Burke**); Area Editor of the Journal of Heuristics (**Burke**); Associate Editor of the *INFORMS Journal on Computing* (**Burke**); Editor of *Theoretical Computer Science* (**Erlebach**); Editor-in-chief of *Science of Computer Programming* (**Mousavi**); Associate editor of IJHCS and *Interacting with Computers* (**Law**); Associate Editor of *Acta Informatica* (**Piterman**); Editor of the *Journal of Discrete Algorithms* 2014-18, Associate Editor ACM J. Experimental Algorithms (**Raman**); Editor-in-Chief of *Recent Advances in Electrical & Electronic Engineering* and Associate Editor of IEEE *Transactions on Human-Machine Systems* (**Zhou**).

Programme committee chairs and steering committee members. Examples include: Chair of the Steering Committee of the EPSRC Observatory for Responsible Research and Innovation in ICT (Orbit) 2017-present (**Burke**); Chair of ICGT Steering Committee and Steering Committee Member of ETAPS and FASE (**Heckel**); Steering Committee member of SBMF and PC Chair of SBMF 2018, Steering Committee member of SPLC (**Mousavi**); Associate chair of CHI 2015 and 2016-2019 (**Law**); General Chair of SustainCom 2020 and Cyberlife 2019 (**Liu**); PC Chair of HVC 2019 (**Piterman**); PC Chair of SEA 2017 (**Raman**); and PC Chair of RC 2018 (**Ulidowski**).

Programme Committee membership of high-quality conferences and workshops. Examples include: ACM CHI 2015-2019 (**Law**), CSCW; FM 2018-2019 (**Mousavi**); MFCS 2015, SEA 2016, ESA 2017, SOFSEM 2019 (**Raman**); SODA 2021 (**Erlebach**); PC Member of FMCAD 2019, APLAS 2019, and FORTE 2019 (Dimitrova); PC Member of SBMF 2018 and CyPhy2018 (**Ringert**); and PC Member of ASE 2018, ICST 2020, and PC Member of ICST 2017-2020 and MUTATION 2016-2019; PC Chair of SBST 2019 (**Rojas**).

Leadership in professional and academic bodies: Chair of the UK Huawei ICT Academy Advisory Board 2017-present (**Burke**); Chair of the EPSRC Strategic Advisory Team for ICT 2016-present (**Burke**); Chair of EASST (**Heckel**); Secretary of IFIP W 1.P (**Mousavi**); Royal Society Newton Fellowship Reviewer Panel (**Raman**); member of the EPSRC Strategic Advisory Network (SAN) 2019-present (**Burke**); member of the EPSRC Equality, Diversity and Inclusion Strategic Advisory Group 2019-present (**Burke**); member of the All Party Parliamentary Group on Artificial Intelligence 2017-present (**Burke**); member of the Expert Panel on Informatics and Knowledge Technology for Research Foundation Flanders 2015-2020 (**Burke**); EPSRC Responsive Mode panel membership (**Erlebach** and **Raman**), and EPSRC

Future Leader Fellowship panel membership (**Zhou**); and reviewing responsibilities for various international funding organisations such as the Dutch NWO, Swiss NSF, French ANU, and the EU ERC.

Awards/Fellowships/Patents: We have won 10 Most Distinguished and Best Paper awards, including: Most Influential Paper Award ICFP 2017 (**Ridge**); ACM Distinguished Paper Award ICSE 2017 (**Rojas**); ACM SIGSOFT Distinguished Paper Award ASE 2015 (**Rojas**); Best Paper Award (SBSE-SS Track) GECCO 2015 (**Rojas**); Best Foundation & ACM Distinguished Paper Award MoDELS 2015; and Best Foundation Paper Award at MoDELS 2020 (**Ringert**).

Burke was awarded Fellowship in the Royal Academy of Engineering (2020), Turing Fellow by the Alan Turing Institute for Data Science and Artificial Intelligence (2018), and Companion of Operational Research, awarded by the Operational Research Society (2017). He is a long-standing FIMA Fellow of the Institute of Mathematics and its Applications, FORS Fellow of the Operational Research Society, and FBCS Fellow of the British Computer Society. **Mousavi** and **Liu** were appointed Fellows of the British Computer Society. **Zhou** gained a three-year Newton Advanced Fellowship, 2017-2020. **Boronat** won the Tool Transformation Contest 2018 with YAMTL. **Rojas** won the Best Demonstration Award at ICST 2017. **Piterman** won the Microsoft Research Outstanding Collaborator Award (2016). **Liu** *et al* were granted a patent for 'A Document Retrieval Method for Peer-to-Peer Online Social Networks based on Knowledge Learning' (Chinese Patent No. 201510955213.4).

Keynotes/Invited Talks. Examples include: Keynote at the International Conference on Concurrency Theory 2015 and Tests and Proofs 2020 (**Mousavi**); invited talk at the ACM SIGMOD/PODS Conference 2018 (**Raman**); keynote at the Frontiers of Algorithmics Workshop 2016 (**Erlebach**); invited talk at the International Conference on Biomedical Engineering and Biotechnology 2018 (**Zhou**); and keynote lecture at the 20th IEEE International Conference on High Performance Computing and Communication 2018 (**Liu**).

Final words. During the REF2021 period, the UoA has substantially strengthened its leadership position in challenge-driven research, particularly in AI and machine learning, algorithmics and formal methods, model-driven engineering, and validation and verification. It established interdisciplinary challenge-led themes—trustworthy autonomous systems and biomedical informatics—and strategically hired and developed staff with strengths in AI, machine learning, and biomedical informatics to support our rapidly growing expertise. As a result, Leicester is now exceptionally well-placed to take on interdisciplinary societal and industrial challenges regarding trust in autonomous and data-driven systems.