Institution: University of St Andrews

Unit of Assessment: 11 – Computer Science and Informatics

a. Overview

The School of Computer Science investigates the theoretical and practical aspects of building effective software and systems. The School brings together 28 academics organised into five broad research themes, each driven by a number of full professors:

- Artificial intelligence (Linton, Gent);
- Computer systems (Dearle, Dobson, Bhatti);
- Programming languages (Hammond);
- Human-computer interaction (Quigley); and
- Systems engineering (Sommerville).

The School's vision is to balance foundational research in core areas (such as programming languages, interaction, and socio-technical systems); taking leading roles in established fields (such as cloud computing); and shaping some of the newest areas of computer science (such as pervasive computing and data science).

To achieve depth within these broad themes, the School's academics organise themselves into small, focused research groups of between two and five academics. Groups have a shared technical interest, allowing them to concentrate on the core scientific issues in their respective domains. They provide a structure within which junior academics can progress their careers within recognised disciplines while receiving support and advice from more senior colleagues; themes encourage collaboration for projects requiring different specialities. Our research groups have well-established reputations and relationships nationally and internationally, including in functional programming, constraint programming, novel interfaces, socio-technical systems, and next-generation internet.

The basic recognition that there are no longer any orthogonal divisions within computer science means many groups and individual staff work across two (and in some cases three) themes. Coupled with the School's intimate size and accommodation, this makes the School agile and allows us to offer a diverse portfolio of research opportunities to our staff and students.

Our research is funded by UK Research Councils, the EU, charities, and direct contributions from industrial partners. Our research facilities include a dedicated human-interaction laboratory, a private cloud computing facility, and hardware prototyping equipment. Our researchers have extensive international collaborations and positions of esteem on editorial boards, research strategy and funding bodies. We support the development of our staff through a strong community atmosphere backed by workload management and regular research leave.

b. Research strategy

The School's on-going vision is to grow its academic standing by achieving a balance between long-term, curiosity-driven programmes and shorter-term, problem-driven research, addressed in collaboration with other academics and industry. In the period since RAE2008, our strategic aims have been:

- To deepen and diversify our funding sources to as to keep the freedom to set and pursue our own research directions;
- To develop the careers and international profiles of our staff and students along their chosen mix of academic and industrial career paths;

- To grow and strengthen our strongest groups; and
- To expand into selected areas where we see substantial synergies and exciting long-term challenges.

Strategic decisions operate across long timescales, so investment in staff and facilities must show the promise of justifying itself over ten years or more, with significant on-going challenges in terms of intellectual content and international significance. We have sought to invest in complementary groups that both add to our existing strengths and have a deep pool of potential staff and research students. Academic, investment, and personnel decisions are therefore of equal significance in strategic decision-making**.** The School regularly reviews its current research work within and between themes, the need to grow activity in emerging areas, and the wider prioritisation exercises undertaken by EPSRC, the EU, and other scientific bodies, benchmarking itself against comparable national and international Schools in terms of publication and funding profiles, student experience and rankings.

i. Research themes and their achievements

Over the REF period the School has encouraged themes and groups to maintain a portfolio of funded and exploratory research projects, mixing established themes with more speculative areas, to ensure that academics, researchers, and students have the opportunity to recognise and explore new areas of research ahead of funding, while developing their careers according to their interests in foundational, translational, or applied research. Over the period we have roughly doubled the proportion of journal papers in our published output. Per-theme scientific highlights include:

Artificial intelligence. Our GAP (computational group theory) and Minion (constraint solver) systems continue to be used to solve outstanding mathematical problems. We have pioneered revolutionary data-driven techniques in human fertility modelling. The main constraint programming conference was held in St Andrews in 2010.

Computer systems. A long-term investigation into causally-consistent messaging systems resulted in a new architecture for scalable messaging systems for environments with serious real-time and consistency constraints, now being deployed by several global companies. Work on next-generation internet led to a new proposed standard that enormously simplifies router management. We developed important formal models for sensor networks, including developing advanced statistical mechanisms for event classification and error detection, which are beginning to be applied in environmental sensing.

Programming languages. A programme of research on cost modelling developed the first systems able to provide accurate cost bounds for higher-order languages. For the first time, this allows both lazy functional languages and those using dependent types to be used in real-time systems. We also developed formal methods for the analysis of concurrent algorithms on real processors, which allowed us to develop a formal description of the concurrency model of ISO C/C++ and prove that it was being compiled correctly to real hardware.

Human-computer interaction. The decision to extend our systems research to encompass human-facing and pervasive systems arose from our strategic review process, and in 2010 we invested in staffing and resourcing a new human-computer interaction theme. Even in this short time, a new methodology for evolving layouts led to the development of new thumb-based keyboard design for mobile devices, and other techniques have generated significant media exposure. We attracted two of the major international conferences in HCI to St Andrews (UIST in interfaces; ITS in surface computing).

Systems engineering. The socio-technical aspects of migrating infrastructure to the cloud led to the development of a cloud migration toolkit, now commercialised by the research students through a spin-out company, PlanForCloud. A collaboration with the Guardian newspaper developed tools for citizen journalism, alongside extensive analysis of social media. Our research in cloud computing and socio-technical systems gave rise to collaborations with Strathclyde Police in dependability analysis, and participation in the LSCITS programme with the Universities of Bristol York, Oxford, and Leeds.

ii. Structure and organisation to promote research excellence

Research pooling. Our national collaborations have been greatly enhanced by the School's leading role in the Scottish Informatics and Computer Science Alliance (SICSA), a co-investment by the University and the Scottish Funding Council (SFC). The research pooling initiative has the overall aims of improving the quality of research in Scottish universities and creating a culture of research collaboration across institutions. The 14 SICSA universities matched from their own resources a funding contribution of £14.5M from SFC. In St Andrews this funding has supported the creation of two Chairs and four lectureships, while the University has demonstrated its own commitment by funding an additional five lectureships – a total investment of over £5M. In addition, SICSA co-ordinates interaction with industry through its business development executive and programmes (AspeKT and CGES) to support commercialisation.

Distinguished lectures. For the past 44 years (since 1969) the School has run a bi-annual series of distinguished lectures, inviting world-leading academics to give an extended day-long series of lectures on selected topics in their field. During the REF period these have included seminars in hardware and software verification (Prof J. Strother Moore, University of Texas US), delay-tolerant networking (Prof Jon Crowcroft, University of Cambridge UK), applied formal methods (Prof Muffy Calder, Chief Scientific Advisor to the Scottish government), and recommender systems (Prof Barry Smyth, UCD Dublin IE).

Community research events. The School supports both a general seminar series and group- and theme-centric seminars involving local and invited speakers. The School has hosted several world-leading individuals for periods of up to six months, funded through SICSA's distinguished visitors programme (e.g., Prof Erik Hollnagel, Ecole des Mines FR; Prof Giorgio Satta, University of Padua IT; Prof Barry O'Sullivan, University College Cork IE).

Investment in physical fabric and facilities. The evolving strategic directions have been supported by improvements in physical fabric and allocation of experimental space. Sensor networks have been deployed for environmental and facilities monitoring, providing a resource that can be used for experimentation, research-led teaching and a means for collaboration with outside bodies. A dedicated HCI lab has been established with appropriate experimental and observational infrastructure, including significant investment in surface computing, visualisation, and novel interfaces. The School built the first private cloud in a UK university in 2009, and this is now used to support a range of computationally-intensive research activities across the School as well as serving as an experimental platform for cloud computing research and for early-stage academic and industrial

collaborations, allowing software to be tuned ahead of moving to the most appropriate commercial infrastructure. This capability was instrumental in developing the cloud migration toolkit to help enterprises transition to cloud-based infrastructure.

c. People, including:

i. Staffing strategy and staff development

Recruitment and development. The School's staffing strategy is uncompromising in its goal to recruit highest-quality staff. This is measured by benchmarking applicants' publication, funding and engagement profiles against what would be expected of someone on a trajectory towards a world-leading career, moderated by their career stage and pathway. Over the REF period the School has recruited 11 new academics bringing new strengths across all five themes:

- ***Artificial intelligence***, in constraint programming (Dr Chris Jefferson);
- ***Computer Systems***, in sensor systems (Prof Simon Dobson), sensor fusion and situation recognition (Dr Juan Ye);
- ***Programming languages,*** in functional programming (Dr Edwin Brady), compilers and concurrency (Dr John Thomson, Dr Susmit Sarkar);
- ***Human-Computer Interaction***, in visualisation (Prof Aaron Quigley) and novel interface design and evaluation(Dr Per Ola Kristensson, Dr Miguel Nachenta Sanchez); and
- ***Systems engineering,*** in social data analysis (Dr Alex Voss) and cloud computing (Dr Adam Barker).

Two of these staff (Kristensson, Dobson) also have substantial start-up company experience.

Personal research fellowships. Several early-career staff have held personal fellowships including Royal Society University research fellowships (Jefferson); EPSRC personal research fellowships (Kristensson); EU Marie Curie fellowships (Kristensson); EPSRC industrial fellowships (Barker); Royal Society of Edinburgh Scottish Crucible fellowships (Barker, Kristensson, Baxter).

Attracting staff of international calibre and diversity. Both professors and three lecturers were recruited internationally (from Ireland, Australia, Canada, and Austria); six of these individuals are non-UK nationals (Irish, German, Swedish, Spanish, Indian, and Chinese); and include one woman and one openly LGBT individual. The School therefore has a demonstrated capacity to attract both foreign academics and emigrants returning to the UK. Five new lecturers were appointed locally from research positions, allowing the School to retain those of our best researchers seeking an academic career path.

Career development. The University's Centre for Academic, Professional and Organisational Development (CAPOD) has created a full range of staff development courses, such as 'using on-line collaborative tools for research' and 'supervising postgraduate students', and CAPOD allocates small grants for attendance at external staff development events. The School provides courses to the University through CAPOD, for example on using social media for research. Staff development opportunities are advertised via electronic Friday Memos and on the CAPOD website, and the University's Careers Centre is available to all staff. Training sessions are provided within the School on a monthly basis, cover topics relevant to both research (e.g., the introduction to the PURE research management system) and teaching.

Mentoring. All new staff are mentored by an existing staff member and (for junior staff) assessed on a bi-annual basis by a probation committee typically including the mentor and two other staff (including one full professor). Probation periods are typically 2—5 years depending on the individual's prior experience. In addition, the Universities of Dundee and St Andrews run a cross-institutional mentoring scheme for early-career academics.

Periodic review. All staff engage in an annual confidential ("Q6") reporting meeting with the Head of School (for academic staff) or their PI (for contract researchers) at which career aspirations and goals are discussed, and a plan of action is agreed. Staff are encouraged develop membership of professional and learned societies to senior and fellowship grades.

Contract researchers. The University of St Andrews values its PGR and research staff as key cohorts in its research community, and the School does not draw social or career distinctions between groups or grades: this greatly facilitates the free flow of ideas and information. However, the career needs of contract researchers differ somewhat from those of academic staff. The University meets all the key principles of the Concordat regarding the recruitment, selection and retention of researchers; the recognition of the value of researchers to the institution; the development of generic and flexible skills; the promotion of personal and career development, the promotion of diversity and equality practices; and the regular review of progress. The success of St Andrews in this area has recently been acknowledged by an Athena Swan Bronze Award, and a European Commission HR Excellence in Research Award. We also actively promote our Stonewall membership and LGBT Charter Mark, and supports Women in Science networking events as a means of ensuring equality across all our practices. Additionally, we assist contract researchers to position their CVs for employment in industry or academia, by facilitating the gaining of teaching experience through small numbers of contact hours, and by encouraging the direction of research towards academic or industrial applications as far as possible in line with the researchers' interests. Contract staff are supported with travel funds to help them build their own independent research network internationally, in addition to funds available from individual research projects.

Research leave. In accordance with University policy, the School is committed to giving all staff regular research leave without commitments to teaching and administrative, on a nominal basis of one semester every four years. We allocate research leave outside the normal schedule for staff working on strategically significant proposals or projects, or who are identified in appraisal as potentially benefitting from additional focused research time. Early-career staff are allocated a reduced teaching and administrative load in their first three years and are encouraged to collaborate with established staff in acquiring first research grants. The School prioritises the use of its independent and overhead research funds towards junior staff and their establishment as independent funded researchers. Staff also have access to personal research funds derived from research contract overheads.

ii. Research students

Research student community. As already mentioned, research students are an integral and growing membership of the School's community. 20% of the School's students are on PGR programmes, leading to the University's strategic priority of increasing the size and quality of its research postgraduate community by building its PGR community to 15% of the student cohort. The School's own activities in creating a supportive and challenging intellectual environment are complemented by the University's new Research Graduate School (St Leonard's College), which has responsibility for ensuring an appropriate training environment for PGRs across the entire University

Recruitment. The School has found it helpful to separate quality assessment and funding issues for prospective students. Interviews are conducted by potential supervisor and one or more other academics, with decisions on student acceptability being made by a committee chaired by the Director of Graduate Studies. Students passing this common quality threshold are then considered for funding, which is competitive. This process makes academic decisions "funding blind", which both helps to maintain the quality of admissions and improves the School's ability to manage

funding sources that have particular constraints on nationality. We aim to meld our various funding streams to fund all our top-ranked applicants, as far as the rules of the different schemes allow.

The School's annual intake of PhD students has grown by around 50% over the REF period, growing the steady-state number of PhD students from 38 to 51.

The School's international reputation attracts international students of the highest calibre with primary and advanced degrees from world-leading institutions (e.g., Technion, Johns Hopkins, Cambridge). The current research student cohort includes students from Turkey, China, Sri Lanka, Thailand, Israel, and the United States, as well as UK and EU countries. SICSA has funded internationally-competitive, nationality-blind "prize" scholarships available to only those demonstrating exceptional potential, and the School has attracted 18 (20%) of the scholarships awarded. The extra cachet increases the value of the scholarships within the international community. A measure of their quality is that *all* SICSA students beyond their second year were named on publications short-listed for REF by their supervisors. The School is further improving its international exposure by focusing recruitment on students at selected US universities, in response to its positioning in the global rankings.

Research-driven teaching. The School's graduate and undergraduate teaching is fully integrated with its research, recognising the research component of both academic and industrial computing careers. As an example, third-year undergraduates all complete a group project derived from the School's research themes: recent examples include developing interactive virtual reality models, and constructing and analysing the results from a building-wide environmental sensor network.

Supervision and training. After reviewing international best practices, the School has moved from the traditional single-supervisor approach for research students towards a more committee-based system. In addition to a primary supervisor, each research student also has a second supervisor and a moderator. Students funded by SICSA also have an additional supervisor from another SICSA institution, which facilitates the discovery of opportunities for further collaboration. Students interact with their committee both informally as required and formally in scheduled reviews and assessments. These include annual poster presentations across the School and bi-annual reporting and assessment with face-to-face interviews (without supervisors present) to catch any management issues.

The SICSA Graduate Academy provides a range of student support activities geared specifically for research students. These include a required course in research methods, generic skills modules tailored specifically for informatics and computer science students (e.g., how to write a computer science conference paper), and an annual PhD conference which is run by the students themselves and allows students to demonstrate their work to other universities, local and multinational companies.

Research students are required to engage with the university's graduate skills programmes, and to take modules in appropriate subjects with which they need experience. The School guarantees to fund students' travel costs for conferences in which they have papers published, and encourages them to form their own international research networks and to identify individuals who might be invited for visits or collaborative activities. Students are also encouraged to consider entrepreneurship, using the resources of the Graduate Academy alongside individual mentoring by staff with commercial experience. The goal is to equip students to follow the career path they choose, without biasing these choices.

d. Income, infrastructure and facilities

Research income. The School has extended its funding portfolio beyond our traditional national

sources (EPSRC), to include European and commercial research funding, aided by the experiences of recent recruits with established and highly visible positions in the EU and internationally. Since RAE2008 the School's research income has grown by 10%, with 20% coming from non-Research Council sources. Success in acquiring EU funding is crucially dependent on access to networks of potential collaborators and consortium members, and an understanding of the processes of research programme formation. Several staff have led or been members of EU projects in mainstream, FET, and other programmes, as well as being involved in devising, managing and assessing research projects and programmes, for example the EU FIRE programme.

The School is supported by a dedicated business development manager, funded by the university and tasked with identifying future and alternative funding sources. This has led to engagements with local SMEs (e.g., Traak, Paywizard, CloudSoft), as well as identifying short-term opportunistic openings that – while hard to exploit effectively – are ideal for exploratory collaborations ahead of project bids.

Infrastructure and facilities. The School occupies two dedicated adjacent buildings, within which it is free to develop the space for teaching and research uses. The School's theme structure has enabled us to plan the development of infrastructure that will be of significant shared value, rather than having to devote private facilities to individual projects. Over the REF period we have developed:

- The first private cloud in any UK university, based on OpenStack and used for both for experiments in cloud computing management and migration, and in support of compute-intensive projects in constraint systems and social data;
- A dedicated user-facing computing lab;
- Extensive hardware prototyping (including electronics equipment and 3D printing) and experimental development space; and
- A sensor network test-bed focused on environmental monitoring.

These facilities have been provided by investment from the University and from a variety of research grants. These facilities are supported by a highly-qualified team of two technicians (including one with extensive hardware development experience) and three systems administrators.

e. Collaboration and contribution to the discipline or research base

Collaboration. The Schools has a large base of cross-School, cross-institutional, and international collaborations. The research grant portfolio includes membership and leadership of Scottish, UK and EU project consortia as well as membership of international and US-based activities. These include:

- Leadership within EPSRC's LSCITS research and training programme (Sommerville);
- Co-management of the CRAWDAD international wireless data archive (Henderson); and
- Leadership within the IETF in developing future IPv6 standards (Bhatti).

The School has developed deep intra-mural collaborations to leverage our research expertise together with that of other disciplines. These collaborations encompass:

- Mathematics and Statistics (in computational algebra and network science);
- Physics and Astronomy (in e-science, advanced materials and manufacturing);
- Chemistry (in large-scale end-to-end experimental data handling and process automation);
- Psychology (in user evaluation and visual perception);

- Biology and Earth Sciences (in sensor networks and environmental monitoring);
- Geography and Geosciences (for automating genealogical linkage), and;
- Medicine (in mathematical modelling and next-generation medical devices).

The School selectively primes these collaborations from its own funds in advance of external funding.

Collaboration within SICSA. The School is a "host" institution in SICSA, which means that – along with Edinburgh and Glasgow universities – it is responsible for SICSA management. St Andrews has had a substantial influence on SICSA, disproportionate to its size (18% of funding with 12% of the academics involved): the School has provided the Director of the SICSA Graduate Academy (Sommerville, 2008-2010), the overall SICSA Director (Sommerville, 2010-2012), and the Deputy Director and Director of Knowledge Transfer (Quigley, 2012-date). Bhatti led the next-generation networks theme (2008-2013) and others have been very closely engaged with the collaborative activities. This has included funding of nearly £40K for international workshops and summer schools in functional programming (Hammond), constraint programming (Gent, Miguel), cloud computing (Sommerville), multi-modal interfaces (Quigley, Nacenta Sanchez), and big data visualisation (Barker, Quigley). The School uses SICSA to develop long-term collaborations within Scotland, for example with Heriot-Watt (Hammond and Brady, functional programming), Glasgow (Dobson and Dearle, sensor networks; Quigley and Nacenta Sanchez, multi-modal interfaces), Edinburgh (Sommerville and Voss, socio-technical systems; Barker, distributed and data-intensive systems), and Robert Gordon (Sommerville, cloud computing). These are then used to drive proposals for national and EU funding.

Strategic influence and scientific recognition. The School's staff are deeply engaged with national and international community activities, key both the building up the discipline and enhancing our profile.

- Prizes, including MIT Technology Review's Innovator under 35 (TR35), Kristensson;
- Charing the leading conferences in various domains including autonomic computing (ICAC); interfaces and interaction (CHI, UIST, ITS, UIU, MobileHCI);
- Editor or associate editor of leading journals in the IEEE and ACM Transactions series including ACM Transactions on Autonomous and Adaptive Systems, Dobson; IEEE Transactions on Services Computing, Barker; ACM Transactions on Intelligent Interactive Systems, Kristensson;
- Membership of strategy leadership groups like UKCRC (Sommerville and Dobson – a number comparable with considerably larger Schools);
- Fellowships or similar status within learned societies including Royal Society of Medicine FRSM, Kelsey; British Computer Society FBCS, Sommerville, Quigley, Dobson; Institution of Electrical Engineers FIEE, Sommerville; Royal Society of Edinburgh Young Academician, Kristensson;
- Over 40% of staff are members of the EPSRC, BBSRC and NERC review colleges, and the equivalent EU and ERC strategy and evaluation panels. Staff also review for non-UK national funding agencies including Switzerland, Sweden, Denmark, the Netherlands, Singapore, Ireland, Italy, Portugal, Canada, the US, Australia and New Zealand.
- PhD examination nationally (including the Universities of Cambridge, Oxford, London, Lancaster, York) and internationally (including Trinity College Dublin, Dartmouth College, Northeastern University, and UPMC Paris 6).