Institution: University of Glasgow
Unit of Assessment: B11 Computer Science and Informatics

a. Overview

Glasgow Computing Science was ranked equal 8th in the last RAE. Since then, the School has continued to prosper, with a strategy of combining world-leading theoretical work with practical applications. Compared to the previous RAE return, the School has expanded - we have 20 new academics and are returning 30% more staff (43 individuals, omitting only one academic). We have graduated more Ph.D. students and brought in more research income per annum, and we have achieved these quality improvements with a significantly younger and more international staff profile. Senior staff have played key leadership roles in Computing Science nationally and internationally. Beyond the REF-returned staff, the School has 32 RAs/RFs and 83 Ph.D. students.

The School's research is driven by 7 research groups: Information Retrieval (IR), Glasgow Interactive SysTems (GIST), Inference, Dynamics and Interaction (IDI), Formal Analysis, Theory and Algorithms (FATA), Embedded, Networked and Distributed Systems (ENDS), Software Engineering and Information Security (SE & IS), and Computer Vision and Graphics (CVG). In 2010, the University undertook a major restructuring to form a more responsive and multidisciplinary organisation, and Computing Science is now one of 7 Schools in the College of Science and Engineering. Glasgow is also a member of the Scottish Informatics and Computer Science Alliance (SICSA) research pool (SFC-funded, £29M, 2008-), with the goal of sustaining and expanding Scotland's research excellence in Computing Science.

b. Research Strategy

The main goals of our research strategy since 2008 have been to:

1. *Sustain and grow excellent research groups*. We rejuvenated our academic staff by hiring early stage researchers and strengthening unifying interdisciplinary themes, while maintaining disciplinary excellence by recruiting world-class quality.
2. *Couple theory with practice*. Many staff focus on problem-driven theoretical topics, which demand new theory to address major challenges of the day, working in an interdisciplinary fashion with top institutes and companies.
3. *Encourage Interdisciplinarity*: We developed two interdisciplinary research themes: *1. Mobile and Sensor Systems,* and *2. Big Data Analytics.* These grew from our existing research strengths, but are supporting expansion into priority areas such as *Big Data* and *Smart Cities*.

1. Sustaining and growing excellent research groups:
Our RAE 2008 strategy was to strengthen our staff in 4 research areas, each of which spans multiple research groups: 1. *Next Generation Internet*, 2. *Multimodal Interaction*, 3. *Modelling and Abstraction* and 4. *Complex Systems Engineering*. We were successful, with SICSA and Glasgow funding bringing 5 Lecturers and 4 Research Fellows into these areas.

IR: Glasgow remains a clear world-leader in the field of Information Retrieval, (2nd university in the world in the top ACM SIGIR conference with 280 papers[1]). The group has 4 academics, 7 RAs and 12 Ph.D. students, and was strengthened with Microsoft/Royal Academy of Engineering Chair in IR (**Lalmas**), the promotion of **Jose** to a Chair, **Azzopardi** to a SL and the appointment of a tenure-track Sensors Initiative Fellow (**Macdonald**), bringing strengths in sentiment analysis and IR in smart cities, an area of current growth.

HCI: Glasgow's Human Computer Interaction research is based primarily in the **GIST** and **IDI** groups. Glasgow remains one of the top HCI sites in the world, with 255 ACM SIGCHI papers (more than any other non-North American site but one[2]). GIST has 5 academics, 2 RFs, 10 RAs and 12 Ph.D. students, with strengths in mobile and ubiquitous interaction (Glasgow's papers

[1] http://dl.acm.org/event.cfm?id=RE160&CFID=242539658&CFTOKEN=68774225 and select affiliations tab.

[2] http://dl.acm.org/event.cfm?id=RE151&CFID=242539658&CFTOKEN=68774225 and select affiliations tab.

make it the *top* university[3] in the world in the leading ACM MobileHCI conference series, with 84 papers), multimodal interaction, diagram evaluation and accident analysis. We recruited a Senior Lecturer, **Vinciarelli**, in the new area of *Social Signal Processing* and two new SICSA Fellows: **J.R. Williamson** on public interaction and social acceptability, **Vazquez-Alvarez** on speech and multimodal interaction. The creation of the **IDI** group was a response to a growing need for new intellectual frameworks to tightly integrate machine learning and sensor-driven human-computer interaction design, especially in mobile settings, so we created a new research group with 4 academic staff, 3 RAs and 13 Ph.D. students, consolidating our strengths in HCI, Systems Biology and Machine Learning. 2 new Lecturer appointments, **Rogers** and **Filippone**, work in the overlap with Statistics and the Life Sciences, as well as with HCI. They collaborate closely with Maths and Stats, Life Sciences and the newly-created Glasgow Polyomics Facility. The University's Sensor Research Initiative funded a tenure-track RF, **J.H. Williamson**, working on sensors and uncertainty in interaction design.

FATA: with 6 academics, 5 RA/RFs and 9 Ph.D. students, FATA is one of the top two groups in Europe in model-checking, world-leading in algorithms for matching problems, and is unique in its practical challenge-driven work to fundamental theoretical research. It has invested in one new Lecturer appointment (**Norman**), a world-leader in probabilistic model-checking, and one RF (**Sevegnani**), a specialist in process algebraic modelling.

CVG: The group has 2 academics, 2 RAs and 9 Ph.D. students, and has re-focussed its sensing work on robotics and autonomous systems applications of computer vision, supported by several large EC grants.

SE&IS: We have deepened our research group in SE by incorporating an Information Security strand and appointing 2 new Lecturers (**Omoronyia**, **Storer**), bringing the team up to 6 academics, 1 RA and 12 Ph.D. students. Key research directions are: Mobile Forensics, Usable security, Resilience of computational infrastructures and Cybersecurity. **Johnson**'s impact in this area is described in detail in one of our impact case studies.

ENDS: There has been major investment in ENDS, which now has 9 academics, 7 RFs, 3 RAs and 21 Ph.D. students. This strengthened the School's profile in two key EPSRC priority areas - Big Data and Multicore systems. A professorial appointment, **Triantafillou**, with expertise in Big Data/information management and distributed systems, formed the IDEAS (Information Data Events Analysis at Scale) sub-group, which links together the IR and the ENDS groups, and consists of a tenure-track RF **Ntarmos**, an RA and 4 PhD students. A new Chair, **Trinder**, consolidates our expertise in SE and the ENDS group, with 5 new RAs and 2 Ph.D. students, creating the Glasgow Parallelism Group (GPG), a thematic grouping of academics and research staff interested in concurrent and parallel programming on multicore systems. Further growth includes 2 new SICSA Lecturers, **Pezaros** and **Singer**, and 2 SICSA RFs, **Tso** and **White**.

The School's research groups have sustained their world-leading quality and productivity. In the ACM Digital library, Glasgow is in the 95th percentile worldwide for citations and 100th percentile for downloads, producing 1200 (200pa) publications, including 545 (91pa) papers in international conferences, 440 (73pa) journal articles, 217 chapters in books, 6 special journal editions, and 18 books. Since 2008, over 48000 citations (Google Scholar) have been made to the publications written by REF-submitted staff - over 1090 per FTE, despite the large proportion (35%) of ECRs.

2. Coupling theory and practice:
The challenge-based approach, where staff develop new theoretical work to address topical problems continues to bear fruit. This includes, e.g. **Manlove**'s Kidney Exchange REF Impact case study, **Brewster**'s funded research on tools to help blind children visualise mathematical graphs and learn to write also won a best paper prize at the top HCI conference, ACM SIGCHI. **Gay**'s Quantum communications modelling research, and applications in joint projects with life scientists, engineers and statisticians and large companies and organisations such as NATS and the NHS are further examples. The success in major EPSRC projects such as Populations (£3.52M),

[3] http://dl.acm.org/event.cfm?id=RE395&CFID=242539658&CFTOKEN=68774225 and select affiliations tab

Homework (£1.1M) and Molecular Nose (£1.45M) demonstrates the role of formal modelling and model-checking in ubiquitous computing, HCI and networking, and molecular biology, and in Section d) we describe the large number of projects with industry and government agencies.

3. Interdisciplinary strategy:
All our new hires are excellent specialists who also cut across research disciplines, so in the REF period the School introduced the unifying topics: *1. Mobile and Sensor systems, 2. Big Data Analytics* which are shaping our on-going development.

Mobile and Sensor systems: This area brings together many of the School and College strengths. Glasgow's mobile and ubiquitous HCI and IR research groups have a wide range of prior projects and publications in the area of *Smart Cities/Future Cities/Urban Informatics*, with more than 50 papers from over £6M funded projects over the last 10 years. This has had recent political and funding prominence as Glasgow City Council won a TSB Demonstrator project of £24M, with further investment from Scottish and UK Government and the EC expected. Glasgow Computing Science is in a strong position to grow this area, and to ensure progress, **Sherwood** was seconded to work directly with Glasgow Council to help them link in to world-leading research and **Murray-Smith** was invited to join the city's *Digital Glasgow Reference Group* which will meet in parallel to the *Digital Glasgow Board* and contribute to strategy development and bring forward ideas, innovations and thinking. FATA members are also bridging topics, bringing model checking and modelling to sensor-based monitoring for communication links. The College of Science and Engineering invested in both leadership and early career research posts, and in enabling multidisciplinary research activity, including a University-wide £3M investment in sensor systems, which has created 8 new Fellowship positions and 15 research studentships spanning all Schools within the College. Within Computing this funded 2 tenure-track Fellows and 1 Ph.D. position. Building on such investment, Glasgow University is now (2013-18) leading an Innovation Centre in Sensors and Imaging Systems (CENSIS). Each Innovation Centre has ca. £30M funding from the Scottish Funding Council (SFC), Scottish Enterprise (SE) and Industry to support industrially-led research collaborations with 12 Scottish HEIs. See Section d) for details.

Big Data Analytics: The ability to sense, process and control systems that generate enormous amounts of data is the key to successfully building and understanding resilient, usable socio-technical systems. The traditional strength of Glasgow in IR, HCI and Inference means that, with the recent expansion of ENDS, Glasgow is unique in the UK in having depth in systems competence in the full set of specialisms needed for Big Data systems (IR, HCI, Inference, complex event processing, Hadoop-based and NoSQL data management systems). We can design and develop all layers of next-generation informatics systems, ranging from the collection, management, analysis, and exploitation of data and information to designing meaningful user interactions with such large-scale data system infrastructures, facilitating the transition from data and information to human-empowering knowledge. This theme will find significant new channels for engaging with industry in the new CENSIS Sensor IC and the Data Lab, as well as RCUK and EC funding sources in this priority area.

c. People, including:

I. Staffing strategy and staff development

Credibility, vitality and sustainability of the research organization. The School has a strong international profile, recruiting the best from around the world, with 18 of the submitted staff coming from outside the UK and 6 staff having had industry careers before joining the School. The number of Category A staff has grown since RAE 2008. There are 3 new Professors (2 new to School), 6 new Lecturers and 7 new Research Fellows. 3 academics retired and 5 moved to other universities or companies. We have a well-balanced School, in terms of age distribution, with a significant increase in excellent young academics since the last RAE, as retiring staff were replaced proleptically and the School grew. 15 meet the ECR definition, representing 35% of our returned staff. See Figure 1 below:

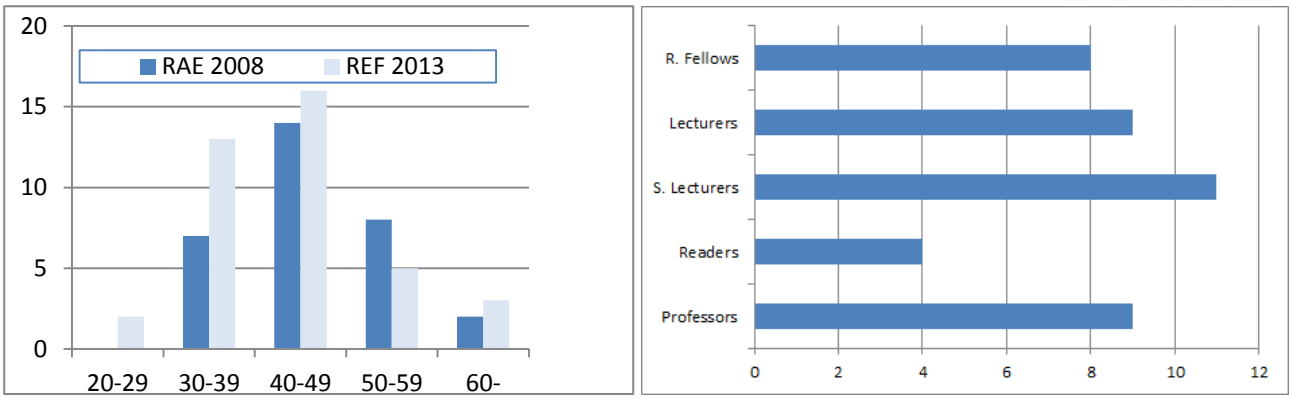

Figure 1: Histograms of REF-returned staff ages (left) and bar chart of academic positions (right)

Fellowships: Staff with active Fellowships and visiting Professorships in the time period include: **Calder**: Royal Society Leverhulme Research Senior Fellow, Royal Society Wolfson Research Merit Award (2011-16, *"awarded to respected scientists of outstanding achievement and potential"*), **Azzopardi** RCUK Fellowship, **Brewster** EPSRC Advanced Research Fellowship, 2003-8, and a Seelye Fellowship from University of Auckland, 2009, **Girolami** EPSRC Advanced Research Fellowship 2007-12, **Renaud** was KIVA Visiting Professor at TU Darmstadt in 2013, **Lalmas** had an RAE/Microsoft Professorship, and **Arafat** an RAE Fellowship. **Rogers** (an ECR) earned a visiting Professorship to Helsinki in 2012. The University has supported our research strategy by fully funding 3 tenure-track Lord Kelvin Adam Smith Research Fellows (**J. H. Williamson, Macdonald** and **Ntarmos**) in the areas of Smart Cities, Sensors and Big Data. The Fellows' migration to full academic positions is dependent upon individually agreed performance criteria. 4 ECR staff have personal SICSA Fellowships and one has an ESPRC Fellowship.

Staff development processes: Staff are reviewed annually, both to guide professional and personal development and assess performance. Outputs from this process inform our promotions and pay rewards processes. This transparency largely corrected previous gender and other inequalities, and evidence now shows that Glasgow University's pay equality is amongst the best in the sector. Promotions follow clear guidelines designed to reward success, and in the REF period we promoted: 1 Professor (via Reader), 6 Senior Lecturers and 2 Lecturers (to Grade 8).

Early career researchers have reduced teaching loads in the first three years (less than half load during the first year), will have no major administrative duties and are mentored by a professor. Any academic submitting grant proposals is given support by senior academics. New staff receive a new computer and necessary resources, as well as a £1k p/a bursary in the first 3 years, to support their research. Research study leave is available for all research-active staff roughly every seven years, and more frequently when staff acquire external funding to support their absence. Flexibility on the use of sabbatical study leave allows multiple shorter periods. Honorary academic staff are given office space, and access to equipment. Our approach is to empower staff to achieve their research goals and hence we have dedicated funds to support staff in pump-priming research collaborations (£10K pa for the School), we have an incentivisation fund (currently £85k pa) which rewards research activity, and further support for attending conferences (£20k pa). The School uses Annual 'away days' to discuss research-specific themes. Glasgow launched the *Concordat to support the Career development of researchers* in 2009 as part of the University's first annual Research Staff Conference.

The University was awarded the *HR excellence in research* award in 2010 by the European Commission, in recognition of its commitment to supporting its researchers' career, personal and professional development and management. The University is amongst only 8 universities in the Russell Group to hold this prestigious award. Every new member of academic staff is paired with a trained academic mentor to support and advise them through a probationary program that can, if desired, lead to a formal Certificate of Academic Practice (CAP). Beyond being a formal teaching qualification, the CAP covers the wider research, ethical and supervisory aspects of academic life. The College of Science and Engineering supports and contributes to the Royal Society of

Edinburgh's *Crucible Programme for support of early career researchers (ECR)* and runs its own talent development programme (also called Crucible) for ECRs. 5 Computing Science ECRs were selected for this multi-day program, which includes externally run sessions in transferable skills from creativity and pitch training to high-impact journal article preparation. Within the School, 7 out of 42 REF-submitted academic staff are female, and we have over 25% female Ph.D. students, which is above average for the subject area. The University has achieved Athena-Swan "Bronze" status as part of its gender equality programme.

c. II. Research students

Research students are valued and nurtured, and they often comment on the friendly nature of the School. Each student has a supervisory team: a first and second supervisor, and a senior overseer. Research students play an active role in research groups, participating in weekly meetings of at least one research group and presenting their research to that group annually. SICSA-funded students (15 at Glasgow since 2008) have a third supervisor from another SICSA university. Student progress is monitored by Research Student Committee via an annual viva. Students submit a substantial annual report and research plan, which is examined by the supervisory team in the annual progress viva. Research Corner is a weekly research meeting, devoted to and run by research students. We also run research student weekends away to integrate new students more rapidly into their research community. Each student has well-appointed office space, receives a new desktop PC system, and has access to computational clusters or any specific equipment needed for their research. The success of the experience can be seen in the increasing numbers of Ph.D. students graduating (75 in this period) since the last RAE (15 pa compared to 13 pa in RAE 2007), with intake increasing (24 pa average in last two years). We currently have a total of 83 Ph.D. students, which is an FTE of 2.5 per permanent academic (the Russell Group upper quartile is 2.3). Over the REF period 37.3% were UK-based, 14.3% from the rest of the EU and 48.4% were non-EU (with no heavy reliance on any one country, although there has been a recent increase in Chinese students). The Research Student Committee oversees funding awards for Ph.D.s attending conferences with an annual budget of £30k.

The College Graduate School, which took over from the Faculty Graduate School in 2010, facilitates the growth of a healthy research community and supports students and supervisors in developing the skills to become future research leaders. It delivers a training programme which promotes best practice in supervisor training and enhances student employability by covering areas such as academic writing, research commercialisation and the skills to engage with the public, media and policy makers. It offers internally funded scholarships which enable staff and students to engage with stakeholders, enhance international mobility and support cross-disciplinary activity. Led by a world-leading researcher and experienced Management Board it is well equipped to address future challenges. Within the Graduate School, the School of Computing Science Research Student Committee funds conference attendance and academic visits. University scholarships are available via a competitive selection process.

The School research groups cover a wide range within the field of Computing Science. Staff have a primary affiliation with one of the groups, but are typically engaged with several, because of natural cross-topic collaboration. Each research group is made up of a number of academics, their RAs and Ph.D. students, and each research group has a weekly seminar series to which we invite internal and external speakers. This provides an environment for staff and students to engage in intellectual deliberations on a weekly basis. In addition, PhD students have a bi-weekly research forum where they get an opportunity to talk to and share experiences with other PhD students in the School.

We have invested significant effort (Murray-Smith as SICSA Graduate Academy (SGA) Director 2010-12 and SICSA Director 2013-) in ensuring that the **SGA** provides excellent training and networking opportunities for Scottish PhD students in Informatics and Computer Science. This provides a rich programme of activities to foster research skills, networking, and transferrable skills, and many of these activities could not be supported by a single institution, working alone. **Annual postgraduate conference:** SICSA funds a 2-day conference, organized by students, for 150 PhD students from across Scotland as a way to network, share research experiences, and

learn how to organize a conference. The programme normally includes poster sessions and research talks by students, keynote addresses by internationally recognized researchers, and research and transferable skills workshops. **Summer schools:** SICSA sponsors several international summer schools each year within Scotland, with fully-funded places available to the students, 2 of which were run in Glasgow. Students can also apply for funding to attend summer schools outside Scotland (9 Glasgow Ph.D. students used this). **Theme events:** SICSA is organized around four broad research themes: Next Generation Internet, Multi-modal Interaction, Modelling and Abstraction, and Complex Systems Engineering. Each theme organizes several Scotland-wide events per year such as workshops and doctoral consortia, providing another opportunity for PhD students to discuss research and obtain advice from researchers outside their home institution. **Distinguished visiting fellows:** SICSA provides support for 10-15 distinguished international researchers to visit Scotland for one week to 3 months each year, and 9 DVFs were led by Glasgow staff. Glasgow students have been heavily engaged in all of these mechanisms both in Glasgow and at other sites.

d. Income, infrastructure and facilities

Income: The School has increased its external award income from £2.62M p/a in the last RAE to over £3.48M p/a in this REF, with £17.4M in new awards since 2008 through 127 separate projects. 28 of these projects were industrially funded (£1.5M). A further £1.14M of consultancy, service projects and industrial secondment brings the total to over £20M. This includes the significant investment from SICSA with £2.85M from SFC coming to Glasgow (although this bid was selected competitively, it does not appear in the statistics for the HESA returns). A further, matching contribution of £2.85M was made by the University (not included in above figures).

Infrastructure and facilities: The School has a strong research ethos and our culture, recruitment policies, advanced level teaching and industrial links are all guided by our commitment to research excellence. We moved into our new £6M building in January 2008. This represents a dramatic improvement in the quality and amount of meeting space, allowed us to consolidate staff from distributed offices, and gave us a state-of-the-art machine room. Additional meeting room space has allowed us to host conferences and regular TechMeetup industry engagement events, and the availability of high quality office and lab space helped us to successfully bid to be a Hub at the new Data Lab Innovation Centre, described in more detail below.

The Research Committee cares for the research environment, developing strategy, supporting grant application processes, publicising research results and opportunities, and pump-priming research (approx. £30K p/a for research committee and £1K per group for minor research costs). The University Research Strategy & Innovation Office and School administrators provide support for the preparation of grant applications and industrial contracts, and support projects once funded. The computing infrastructure within the School is supported by a team of 4 system support staff and 3 technicians.

Investments: Machines for academic staff, RA & Ph.Ds. are renewed on a 3-year cycle, with a budget of £41k p/a (53 machines p/a). SICSA has supported investment of £200k in equipment, primarily for research by new staff in the areas of *next-generation internet*, *modelling and abstraction* and *multi-modal interaction*. The School provides several computational clusters (£425k spent, with £80k new investment planned) and a large storage area network. IT Services provides state-of-the-art networking, storage, and computational facilities for all university members with additional specific investments of £456k from the School in upgrades in the REF period. Gigabit Ethernet and Wireless LAN are provided throughout (recently upgraded at a further cost of £146k, to include ubiquitous wireless access to Eduroam throughout the school). The School network backbone was upgraded from 10Gbps to 40Gbps and the School's connection to the rest of the campus from 1Gbps to 10Gbps). To support our collaborative projects we have installed a £31k, dual LED monitor, dual HD camera video-conferencing suite capable of supporting the standard protocols as well as Skype.

The School and College have provided significant (ca £90k) multicore hardware systems in support of the MACDES area: 64-core, 512GB RAM, 7TB disc SMP; 128-core Beowulf cluster; numerous

8-16 core personal development systems. The CVG group invested in a full-scale two-armed industrial robot with rotatable torso, an actuated binocular vision system to be equipped with touch-sensitive anthropomorphic grippers. ECRs are supported by the College small equipment fund (£0.5M, supplemented by an EPSRC award) purchasing items both for individual and shared use. Within Computing this funded ca £32k for **Pezaros**, **J.R.Williamson**, **Singer** and **Omoronyia**, including server systems, multitouch displays and laptops.

We have maintained a cluster of 40 nodes to support the Terrier IR system, since 2008. This has allowed researchers and research students to have access to storage and processing capabilities suitable to conduct research on a par with commercial research labs. As Information Retrieval focuses on the processing of large volumes of data, we have over 35TB of fast reliable storage, as well as another 35TB of storage as part of a Hadoop distributed file systems that permits MapReduce jobs. On top of this, we have developed a rich software infrastructure to support state-of-the-art information retrieval research, based around the Terrier platform.

Reflecting developments in interaction design research we have invested in a new workshop (led by a SICSA Fellow **J.R. Williamson**) that allows research staff and Ph.D. students to develop expertise in electronics prototyping, and provides a workspace and fabrication studio for building hardware and physical interaction objects, with embedded sensing. This includes a new 3D printer for rapid prototyping, electronics lab equipment, a printed circuit board (PCB) rapid prototyping machine, large touch displays and minor electronics consumables.

Research portfolio and future plans: Inspecting the diversity of the £20M in new awards since 2008, we can see a wide range of funding sources. This included 127 separate projects. 28 of these projects were industrially funded (£1.5M). 41 were EPSRC projects with a value of £9.2M and 11 were new EC-funded projects, worth £3.47M. Weighting annual income by the staff in place each year during the REF period (as we have recently expanded significantly, dividing by current FTE would give a misleading impression) this is ca £103k per FTE pa (c.f. Russell Group median of £82k per FTE p/a).

Large current EPSRC grants include the £3.52M Populations programme grant *(A Population Approach to Ubicomp System Design*) led by **Chalmers** and **Calder** at Glasgow together with UCL, *Anyscale Applications* £1.16M (led by **Singer**), and **Vanderbauwhede** leads the £1.54M *Exploiting Parallelism through Type transformations for hybrid manycore systems.* **Gay** leads Glasgow's participation in the £3.96M EPSRC Programme grant *From data types to session types - a basis for concurrency and distribution*, in collaboration with Edinburgh and Imperial. During this REF period, the School has also been heavily involved (about 23% of our funding) in European research, including 18 active COST actions, EC Networks and Projects. Glasgow leads on some of these: **Vinciarelli** coordinates the €6M, 12-partner *SSPnet* in the exciting new area of social signal processing and **Gay** leads the BETTY COST action.

Industrial Ph.D. funding: We have a tradition of exposing our students to foreign research experience, and have arranged internships with companies such as Google, Yahoo, Microsoft, B&O and Nokia. The Chinese University Scholarship programme has funded 5 positions since 2008. The School has defined a policy for 50% support for industrially co-sponsored Ph.D. students. This has been very successful, and has boosted our interactions with industry significantly, ensuring long-term engagement with a company which survives re-organisations. The mechanism has been used with Nokia, Bang & Olufsen (B&O), Freescale, Strathclyde Police, National Australia Group and Sciencesoft, for a total of 15 studentships (an impressive proportion of our total of 85 students). Nokia sponsors two of their own research staff and predominant Russian search engine Yandex sponsored one staff member to study for a part-time Ph.D. in Glasgow.

Consultancies & Professional services: The School's reward structures encourage staff to engage with industry and government by providing expert advice and consultancy up to 30 days a year. Since 2008 staff have engaged in 35 consultancies with 21 different companies/agencies, with a total value of £348k. These were typically focussed projects giving specific advice,

evaluating or improving products. Staff have also had £140k of seconded work with industry, and £1.085M of academic positions with industrial or government sponsorship (including a Chair in Information Retrieval sponsored by Microsoft and the Royal Academy of Engineering). The companies involved included world-leading firms such as Microsoft, Nokia, Google, Cisco, B&O, Yahoo, legal partnerships, health boards, start-ups and government agencies. For example, Johnson's European Network Information Security Agency (ENISA) consultancy project set up the European Cybersecurity incident reporting system that all EU member states now have to use to meet requirements of Article 13a of the Framework Directive.

Innovation Centres: The Scottish Funding Council has invested in a number of Innovation Centres (ICs). These are intended to simplify the research landscape for industry, and our main focus is to use them to strengthen Scotland's local industry and transfer its world-leading research in informatics and computing science into the marketplace. The School was a participant in two of these, CENSIS and the Data Lab. *CENSIS* is a Scottish Innovation Centre in Sensor & Imaging Systems, which was opened by the University of Glasgow together with 11 Scottish universities and 22 industrial partners. With funding of £30M from SFC, SE and industry, this will provide a mechanism for engaging with industry in the area of sensors. One key topic of focus will be wireless networks, research we previously did within the scope of the Institute for System Level Integration. The *Data Lab Innovation Centre* will be a world-class Data Science Innovation Centre, generating significant economic, social and scientific value. It will link SICSA institutes with local industry and government in addition to our existing international profile. The Data Lab aims to transform the nature of collaboration between industry, public sector and academia in data science. This IC will have an expected turnover of £30M in the next 5 years. The Data Lab will have a Hub based within our new building at the School of Computing Science in Glasgow, and should lead to ca. £5M in collaborative projects with industry in Glasgow in the next 5 years.

Growth in Singapore: We are building on the new institution of the University of Glasgow, Singapore (UoGS) to access research students and industrial collaboration in the rapidly growing Asian market. There are 2 UoGS Computing Science staff who are both teaching and research active, and we plan to expand our PGR student numbers with joint supervision from both UoG and UoGS staff, primarily with Singapore-based industry employees. These (50 over the next 5 years) are financed by the Singapore Economic Development Board.

e. Collaboration and contribution to the discipline or research base

Leadership examples: The School has a prominent role in leading UK Computing Science, having provided two recent Chairs of the UK Computing Research Committee (UKCRC), **Calder** (Chair 2009-11, and Executive committee member 2004-11) and **Sventek** (2012-). **Calder** was also Chair of BCS Academy Research Committee (2011-13) and was a member of EPSRC's Technical opportunities Panel (2009-11), and the Scottish Enterprise Technology Advisory Group (2012-). **van Rijsbergen** chaired the European Research Council CS panel (2009-10). **Calder** is on the Scientific Steering Committee of the Isaac Newton Institute for Mathematical Sciences, Cambridge (2010-), and the Scientific Advisory of the EPSRC/GCHQ Cyber-Security Research Institute (2012-). She chairs the Scottish government *Cyber Security and Resilience Board* (2012-) and is a member of the Data Management Board (that has a similar role to the UK Transparency Board).

Calder was appointed Chief Scientific Adviser (CSA) to Scottish Government in 2012. This a Director-level position providing independent advice at cabinet level to Ministers across all portfolios but most frequently to the Minister for Learning, Science and Scotland's Languages and to the Cabinet Secretary for Education and Lifelong Learning. She held 11 public lectures, bringing computational thinking to a wider audience.

The School has worked hard to change the teaching of Computing Science in Schools. **Cutts** has been involved in extensive engagement with school Computing teachers, and has been successful in changing Scottish school qualification processes. This is already being supported onwards via his 60% secondment from 2013-15 to support development of government education policy via a grant funded by the Scottish Government, and administered by the BCS. He will lead the new

Computing Science CPD programme for teachers. **Calder** chairs the Scottish Government *Schools Excellence in ICT* working group, (2012-), and the *Computing Science Curriculum and Continuing Professional Learning* Steering and reference groups (2013-). She was also a member of the Royal Society *Computing Science at School* working party (2010-12).

Full Programme or Conference Chairs: 28 world-class conferences, including premier ones such as ACM SIG CHI were chaired by Glasgow Computing staff, and 77 keynote/Plenary talks at major conferences were given.

International board membership: Sventek was a member of advisory board to EPFL Informatics and Communications School (2001-10), and a member of a review panel for KAIST CS department (2010). **Murray-Smith** was on the Nokia Scientific Advisory Board (2008-09), and the IAB for Aalto University Centre of Excellence (2012-). **Trinder** was a Romanian RAE ICT Panel Member. **Johnson** Chaired the Scientific Advisory Board for the €3 billion EC SESAR programme on air traffic modernisation, and acts on the Advisory Panel to the UK Home Office CONTEST-INSTINCT Counter Terrorism Programme, the UK Department of Transport Cyber Security Risk Assessment Working Group (which feeds directly to the Cabinet Office to inform COBRA decision-making and planning), and to EUROCONTROL on Cyber Security and on degraded modes of operation in aviation. He has also joined the Maritime Cybersecurity working group. **Calder** is on the Advisory Board for the EC FET programme. Younger academics are already making an impact, e.g. **McGee-Lennon** is on the National Telecare and Telehealth Advisory Board, and **Storer** is on the Cyber Security Resilience Advisory Board for Scotland Higher Education and Research.

Panel members or reviewers for academic institutions: in Denmark, Sweden, Finland, Poland, Ireland, Romania, Hong Kong, Vietnam, Saudi Arabia, USA, Canada. School staff acted as external examiners outside the UK in 36 Ph.D. defences.

Prizes and awards: Calder: Order of the British Empire (OBE, 2011) for services to Computing Science, became a Fellow of the Royal Academy of Engineering in 2013. **Brewster**: Best paper awards/nominations ACM ICMI 2008, ACM CHI 2008, CHI 2010 (2 awards), CHI 2011, MobileHCI 2011 (2 awards), MobileHCI 2012, RepliCHI award 2013. **Johnson**: Best paper International Systems Safety Society (2008 and 2009), Distinguished Research Award International Systems Safety Society (2010). **Vazquez-Alvarez** (ECR): Best paper ACM CHI 2011. **Sventek**: Best performing solution to DEBS 2012 grand challenge. **Azzopardi**: Best paper at European Conference in Information Retrieval (ECIR 2012). **Jose**: Best paper awards at IIIx 2008, ACM MMM 2011, ECIR 2013, ACM SIGIR 2010 (best student paper). **Cockshott**'s work on mine-clearing systems won an EPSRC ICT Pioneers Prize in Transforming Society, and a Thales Scottish Technology Prize 2010. **Prosser** received the 2011 ACP Award for research excellence in constraint programming.

Singer, **Vanderbauwhede** and **Trinder** participated in the *"Many-core Architectures and Concurrency in Distributed and Embedded Systems*" (MACDES) framing workshop conducted by the EPSRC, which led to the £5M *System Approaches to Distributed and Embedded Architectures* (SADEA) call. 3 of the 5 funded SADEA proposals (from 16 bids) were led by these Glasgow staff, with a total value of ~£3M.

Interdisciplinary collaboration is encouraged and widespread. The overwhelming majority of papers are multi-author, with many co-authored with external or non-CS authors, reflecting a high level of collaborative and interdisciplinary work. Over 30% of grants have been with other Schools or Institutions. For example, the £3.52M Populations (**Chalmers, Calder, Girolami**) project brings together Formal methods, Statistics and HCI at Glasgow and UCL. **Rogers, Filippone, Calder** and **Miller** are transferring ideas from machine learning and from formal modelling and analysis to the systems biology and engineering areas, together with the life sciences and biomedical engineering researchers in Glasgow. There are strong links with the School of Psychology, and **Brewster** works together with psychologists on multimodal interaction. **Vinciarelli** is shaping the field of Social Signal Processing at a European level, coordinating an EC network of excellence, bringing Psychology and Computing together. **Murray-Smith** combined interaction design and machine learning with Brain Computer interaction, with European partners in the TOBI BCI project. The

EPSRC Homework project (**Sventek, Calder**) linked Networking, HCI and policy-based network management across multiple institutions. In 2007, the University established the Kelvin Smith Scholarship scheme for interdisciplinary postgraduates. This scheme focuses on the creation of research partnerships between members of staff who have not previously collaborated, and are in different discipline areas. During the REF period 5 Ph.D. students were funded by the Kelvin Smith scholarship. Glasgow also invested ca. £3M in an internal Sensor Systems initiative for interdisciplinary work, which has funded 2 tenure-track Research Fellowships and one Ph.D. studentship within the School. SICSA has supported Scotland-wide collaboration, via research themes, SICSA student supervision, visiting fellowships and joint research. Glasgow has played a leading role in SICSA, as one of the three Host institutions (along with Edinburgh and St Andrews), with **Murray-Smith** SICSA Director 2012-14, Scottish Graduate Academy Director 2010-12 and member of the AspeKT Board. **Brewster** leads the SICSA *Multimodal Interaction* Theme, **Chalmers** leads the *Smart Cities* Theme, and **Perkins** and **Norman** co-lead the SICSA *Next Generation Interne*t and *Modelling & Abstraction* Themes respectively. **Gay** leads the QNet EPSRC Network and co-started the Scottish Programming Languages Seminar and the QUISCO network. **Murray-Smith** had a joint appointment with the Hamilton Institute (a multidisciplinary institute bridging mathematics with applications in ICT and biology) from 2001-08. **Calder** has been involved in joint projects with Biochemistry and Engineering on the *Molecular Nose* EPSRC project, and an EPSRC project on *Modelling Signalling Pathways* together with Edinburgh University and Cancer Research UK.

Research collaborations with research users, including industry users: The School hosts monthly TechMeetup events which link industry and academia, attracting 50-100 participants. This exposes Ph.D. and undergraduate students to the start-up community, and gives the School insight into commercial priorities. The Innovation Centres in Data Science and in Sensors described earlier will be a key element of the School's engagement with industry and government.

Glasgow staff have collaborated with world-class companies and with government agencies. These funded projects have changed research directions in both the School and in industry. **Sherwood** was seconded to Glasgow City Council to support their Future Cities project. **Murray-Smith** was seconded 50% to Nokia Denmark for a year in 2008-09 to bring sensor-related innovation to their products. This led to Nokia releasing a phone with a key selling point based around a research paper written by **J.H. Williamson** and **Murray-Smith** in 2006. Collaboration has also included government bodies, e.g. **Manlove** has worked with the NHS to implement software for finding kidney paired exchanges, which is now used throughout the UK. **NATS,** a global leader in air traffic control services, funded **Calder** to develop predictive stochastic models for their sensor driven systems for navigational services. Deliverables included a large-scale stochastic model and its analysis, and a portable web-based interface for engineers, with collaboration focussing on changing working practices. The CVG group collaborates with commercial and governmental organisations, for example winning: a Medical Futures Award (in collaboration with Yorkhill Hospital, Glasgow NHS), and an R&D Award received by Freescale Ltd. in the National Microelectronics UK Awards. **Trinder's** systematic evaluation of Erlang for commercial distributed software engineering has significant impact in the developer community, e.g. slide-sets had 16K views on Reddit; Motorola product groups adopted Erlang; a project software component became a mission-critical product; and Erlang evangelists became established within Motorola.

The **SICSA Knowledge Exchange Directorate** increases the economic and social impact of university research by working with companies of all sizes to transfer advanced research to industry, by informing researchers of current industrial problems, and by providing industrial and entrepreneurship training for researchers. It offers a broad programme of activities and, in 2012-2015, £410k funding to encourage exchange between researchers and business, targeting Ph.D. students and other early stage researchers, and Glasgow's engagement is described in detail in the Impact Template.