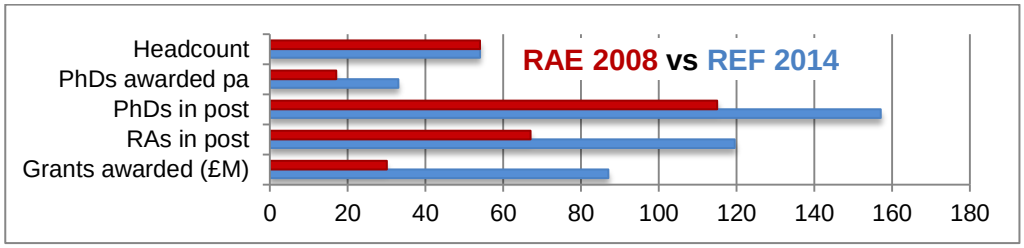
Institution: Imperial College London
Unit of Assessment: 11 Computer Science and Informatics
a. Overview

More than 50 academics, 120 researchers, 150 PhD students and 610 taught-course students, comprise the Department of Computing, making it one of the largest departments in the Faculty of Engineering at Imperial. Our affiliation to this faculty is a strong indication of our commitment to Computing as an Engineering discipline. The Department is organized in five research sections: Distributed Software Engineering; Logic and Artificial Intelligence; Programming Languages and Systems; Quantitative Analysis and Decision Science; and Visual Information Processing. We take pride in our collegiality and the culture of strong collaboration within and between sections.

Our ethos is based on research excellence. We value innovative research in core and applied computing, translation of such innovation to solve real-world problems, and curiosity-led and high-risk endeavours unobstructed by organisational hierarchies. Across our broad research base, we promote and foster excellence through strategic mechanisms such as:

- **Attracting and Developing Leaders:** By offering attractive and competitive rewards in an exciting environment, we are able to recruit and retain international academics of the highest calibre. Our focused research support helps secure large, highly competitive grants and fellowships; during the REF period, our staff obtained 35 major awards including 13 external fellowships as well as 5 prestigious Imperial College JRFs.
- **Expanding the Research Pipeline:** Research funding awarded increased by 180% over the RAE period, with 79% more researchers in post in July 2013 than in July 2007. This has been achieved with a natural turnover of academic staff. Our Department is vibrant and sustainable – more than 20% of academic staff have joined the Department since 2007.
- **Training the Next Generation of Researchers:** We compete for the very best PhD candidates globally, awarding full fees and stipends to 85% of our PhD students. Our PhD student population increased by 36% between July 2007 and July 2013. The average number of PhDs awarded per annum increased by 94%.
- **Improving the Research Environment:** An extensive roster of international academics and industrial research scientists visits our department and actively contributes to our dynamic research atmosphere. We have state-of-the-art computing facilities, a substantial cloud-computing infrastructure, and have expanded our research space by nearly 50%.



The bar chart shows measurable successes since RAE 2008 as a result of our nurturing strategy.

b. Research Strategy

b. I. Departmental strategy since 2008

We aim to remain among the leading departments in the world for research and education in our discipline. To ensure our place, the objectives of the Department are:

- To pursue research excellence and innovation in core Computer Science;
- To carry out world-leading interdisciplinary research which recognises that Computer Science is pervasive in all areas of society;
- To develop novel, sound and applicable computing techniques to meet the evolving needs of science, industry and society;
- To pursue innovative education based on foundational research that fosters technical excellence, originality and breadth of vision in its students.

To meet our objectives, our strategy has been to sustain a mixture of fundamental curiosity-driven and applied problem-driven research relevant to the College's strategic themes of Healthcare, Security, Energy and the Environment. This strategy is realised through a focus on emerging research challenges in core Computer Science and increased interdisciplinary research by collaborations within, and external to, the College. Tactically, this has been accomplished by encouraging large, long-term research projects (see **section d**), which are mostly collaborative (Programme Grants, Investigators *Gardner, Kelly, Rueckert, Yang, Yoshida*), often inter-disciplinary (ERC Synergy award, Investigator *Rueckert*), and supported by diverse sources of funding. This is reinforced by investment in people and infrastructure (see **sections c** and **d**).

Our research strategy is reviewed annually at the departmental away day, where discussion is focussed on specific themes or questions. For example, in 2013 some of our recently appointed academics discussed their visions of computer science in the future. The departmental Executive Committee, consisting of the Head of Department, Directors of Research, Teaching, Postgraduate Studies, Industry, Operations, and their Deputies agree the overall research strategy; the Department Research Committee is responsible for its implementation. The Director of Research chairs the Research Committee and all academics are actively encouraged to attend and participate.

We have achieved our RAE2008 objective of hiring at least one new lecturer per year – we made 12 new appointments over the REF period. In our RAE 2008 submission we identified four research themes on which to focus application oriented and interdisciplinary research: Autonomous Systems, Ubiquitous Systems, Internet Technology, and Systems Biology. The outcomes of this focus are described below, showing both the effectiveness of that focus and its transformation into the research challenges that reflect the rapid pace of technology change in Computer Science.

Focus on emerging research challenges in core Computer Science

The cross cutting challenges we tackle are in: ***1) Data to Knowledge*** – spanning a wide breadth of topics including large-scale data management, optimisation, data-level machine learning, knowledge representation and knowledge-level machine learning***. 2) Algorithms*** – problems that have traditionally been unsolvable due to state space explosion. These include developing new algorithms to solve problems in domains ranging from computer graphics and vision to simulation and model checking. ***3) Correctness and Performance*** – problems that range from foundational issues of computer security, through verification of GPU, web-based and autonomous multi-agent systems, to performance optimisation for software and hardware systems. Much of this research is done collaboratively (over 70% of grants) both within the Department (39% of grants have at least two investigators from the Department) and in our research communities.

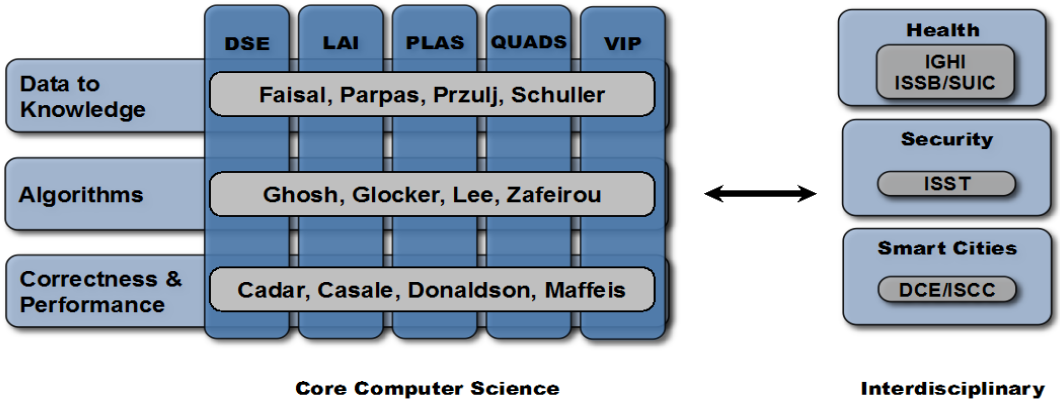


Figure 1: Strategy with new appointments and interdisciplinary institutes (acronyms below).

Focus on interdisciplinary research across departmental boundaries

The College has fostered cross-disciplinary research by creating cross-faculty Research Institutes in key areas of strength. The institutes provide a framework for collaborative working, raising the profile of research in an area. The Department has grasped the opportunity to solve Computer Science problems that arise beyond our traditional boundaries by providing scientific and academic leadership for three of the five College institutes:

- ***Institute of Global Health Innovation*** (**IGHI** - established 2010, Deputy Director: *Yang*). It includes the ***Hamlyn Centre*** (established in 2008, Director: *Yang*) for biomedical robotics, imaging and sensing. Developments include the i-Snake articulated medical robot that addresses key limitations of current rigid instruments and is likely to revolutionise future minimally invasive surgery.
- ***Institute for Security Science and Technology*** (**ISST** - established 2008, Director: *Hankin*, Associate Director: *Lupu*) is an Academic Centre of Excellence in Cyber Security Research; Gardner leads a new GCHQ/EPSRC Cyber Research Institute (see **section e**) to find new ways of automatically analysing computer software to reduce its vulnerability to cyber threats.
- ***Institute of Systems and Synthetic Biology*** (**ISSB** - established 2008, Management Board *Muggleton*). It includes the **Syngenta University Innovation Centre** (**SUIC** – established 2008), hosted in the Department. Muggleton's machine learning techniques, using SUIC data, led to food webs, which are key to understanding the effects of agriculture on the environment and are a very useful indicator of biodiversity.

Additionally, we provide scientific leadership in Smart Cities – responding to the research challenges arising from making city services more adaptive by harnessing real-time user data and city infrastructure data. This leadership includes: the ***Intel Collaborative Research Institute in Sustainable Connected Cities*** (**ISCC** – established 2012 with UCL, Imperial Director *McCann*), the ***NEC Smart Water Systems Lab*** (**SWSL** – established 2012, Computing PI *McCann*) and the ***Digital City Exchange*** (**DCE** – established 2011, CoIs *Guo* and *Hankin*).

Focus on large-scale, high-prestige projects and diversification of research income

In order to maximise our research effectiveness, we have increased our focus on large, longer-term research projects. These projects provide a valuable mechanism for collaboration and help to address major research challenges. Marked benefits for researchers include funding stability that we use to be creative and to address more difficult challenges; ability to enable research activities to reach a critical mass; lower overhead of administration costs and less overall proposal development effort. We have also made a particular effort to establish and strengthen long-term collaborations with companies such as IBM, Intel, NEC, Syngenta, Dyson, Microsoft, and Google, as well as with SMEs such as Maxeler, Ocado, and Codeplay, particularly via EU projects, the International Technology Alliance and the Smart Cities initiative. (**Sections c** and **d** detail both the enabling support and provide evidence of the success of the focus.)

b. II. Future strategy

The general strategies outlined above will continue to inform our planning and management, and will be built upon and extended. We expect to sustain a mixture of fundamental curiosity-driven and applied problem-driven research relevant in strategic areas. To do this, the Department will continue to invest in our most crucial asset, namely staff (see **section c**). This investment will include regular, targeted academic recruitment, timed to coincide with the American job cycle, since we have found in the past that this increases the number of high quality applicants.

We plan to extend our collaborations with industry. In addition to existing research centres (Intel, NEC, Syngenta) in the Department we are planning to engage in new areas, as part of the translational research developments at the new Imperial West campus. We have just signed two MoUs with Huawei and Dyson. The intention is to develop joint innovation labs to use Big Data to enrich and improve life with Huawei (lead: *Guo*) and in robot vision with Dyson (lead: *Davison*).

We aim to be initiators and leaders of new research fields, rather than followers; we encourage our staff to explore speculative, high-risk ideas that may establish such leadership. For example, we are augmenting traditional artificial intelligence with statistical machine learning. We will help with horizon scanning activities and continue to be opportunistic, identifying promising new research fields, which suit our skills and interests, as well as recognising topics, which are becoming less productive. We plan to increase our research activity in Security, Interdisciplinary Healthcare, and Connected Cities given our current grant portfolio and recent appointments. Another area for increased future research activity is Data Science; there are plans for the creation of a College-wide Data Science Institute (lead: *Guo*) that addresses emerging challenges in this area. Our curriculum revision processes will continue to integrate new research content to deliver leading edge and exciting education to our next generation of scientists and engineers.

b. III. Research section strategy: aims and achievements

The Department is organized into Sections that capture the evolving focus of our research. Since RAE 2008, the number of sections has reduced from eight to five, each reflecting broader focus, recent collaborations and more balanced numbers. Our guiding principle is to empower academics, at every level, to set their own research agenda and the function of the Sections is to provide support and coordination. Research collaborations and projects often cross sections. The aims and exemplar achievements of each section are summarised below.

Distributed Software Engineering research addresses the challenges of building dependable, adaptive and secure distributed systems. The Aedus2 EPSRC platform grant has provided baseline funding over most of the REF period. Other major grants include IBM led ITA funding from the MOD/US Army over 7 years (*Lupu, Pietzuch, Russo, Sloman, Wolf*), an ERC starting grant (*Uchitel*) on **partial behaviour modelling**, plus the recent funding for the Intel and NEC centres resulting from work on **mobile ad-hoc and sensor networks** for urban environments (*McCann*). Highlights include a platform for **model-driven generative programming** to facilitate experimental design and execution management for distributed systems (*Wolf*), predictable **data centre network analysis** for inclusion in Microsoft's Azure platform (*Costa*), middleware for **secure event-processing** based on information flow control models (*Pietzuch*), tools for analysing **firewalls and network protocols** using logic-based reasoning (*Lupu*, *Russo*), and Ponder2, a toolset for **adaptive policy-based management** of distributed and ubiquitous systems (*Dulay*, *Lupu*, *Sloman*). Significant achievements in **requirements engineering** include the synergistic use of inductive logic programming and abduction with model checking techniques to support the synthesis of scenarios and goals into operational requirements (*Kramer*, *Russo*, *Uchitel*).

Logic and Artificial Intelligence research encompasses foundational studies in Logic and a variety of Artificial Intelligence disciplines. The work has led to several best paper and runner-up awards at leading international conferences (including AAMAS, ETAPS, EATCS and ICILP) and attracted three Marie Curie fellows. Novel research in model checking methodologies for the **verification of autonomous agents** has found application in autonomous vehicles, service-oriented computing and security (*Lomuscio*, awarded an ESPRC Leadership fellowship). Results in **inductive logic programming** have been applied to problems in bioinformatics (*Muggleton*, awarded a RAEng chair first supported by Microsoft and now by Syngenta). Output on **machine learning** applied to bioinformatics has been boosted by the recruitment of *Przulj* whose pioneering work on biological network analysis, modelling and alignment has helped her to secure an ERC starting grant. In addition, the recruitment of *Faisal* (joint appointment and returned with Bioengineering) and *Schuller* has strengthened the section's expertise in **statistical machine learning** approaches. *Schuller* has recently been awarded an ERC starting grant.

Quantitative Analysis and Decision Science research ranges from optimisation, performance engineering and knowledge discovery to quantitative verification and security. The work of the section has led to five best paper awards at major international conferences (Middleware, QEST, SPECTS, ICPE) and helped to attract two prestigious Imperial College JRFs (*Wiesemann* and *Casale)*. *Wiesemann* is now lecturer in the Business School while *Casale* joined the Department as lecturer, significantly strengthening the group's pioneering work on **performance engineering**. Significant achievements include novel fluid and compositional analysis techniques with application to performance, storage and energy modelling. Their open source software PIPE2 (pipe2.sourceforge.net), has been downloaded more than 100,000 times over the past decade. In **computational optimisation** the section has pioneered research in decision making under uncertainty. In 2011, *Parpas* (supported by a Marie Curie Career Integration grant) joined the group to bring additional expertise in the area of multi-scale modelling. The section's research in **discovery sciences** has led to the development of the tranSMART system for translational informatics that is now becoming the standard open source platform for medical research and pharmaceutical industry. The success of this led to the €24M eTRIKS European project (*Guo*, PI) involving the participation of 12 major pharmaceutical companies and medical research institutions.

Programming Languages and Systems is a new section that addresses theoretical and practical challenges in languages and architectures to ensure fast, efficient and correct software and hardware. Its work has led to more than ten best paper/artefact awards at major international conferences such as OSDI, ESEC/FSE, ESOP and FPL. The section's work on **hardware and**

accelerator architectures has been highly successful and supported by EPSRC platform grants (*Luk*). Its impact is felt beyond academia and has led to a start-up company (Maxeler, founded by *Mencer*). It includes quantitative characterisation and optimisation of GPU and FPGA architectures. A second line of research focuses on **software correctness and reliability.** This research led to concurrency-aware formal verification techniques for checking correctness at multiple levels of abstraction and has been applied to the detection of bugs in software by companies such as Yahoo, Facebook, Microsoft and Airbus. Funding includes two EPSRC programme grants (*Gardner* x 2), a RAEng/Microsoft research chair (*Gardner*), as well as EPSRC Advanced (*Calcagno, Gardner*) and EPSRC Career Acceleration (*Maffeis* – now a lecturer) fellowships. A recent recruit *Cadar* was awarded EPSRC Early Career fellowship in 2013 to work on novel tools for automatic test case generation and defect detection. The third strand of research focuses on **programming languages and software performance optimisation** and includes session types, a new paradigm for concurrent and distributed programming; and programming models and abstractions for automatic offloading to heterogeneous multi- and many-core architectures. The group has been strengthened by the recruitment of *Donaldson* (with EPSRC postdoc fellowship). This work is supported by an ESPRC platform grant (*Kelly*), part of two EPSRC program grants (*Kelly, Yoshida*) and an EPSRC Advanced fellowship (*Yoshida*). Applications include a protocol language used by Ocean Observatories and the optimisation of AAA video games by Codeplay.

Visual Information Processing research covers a range of topics including vision, graphics, intelligent behaviour understanding, and biomedical image computing. The work of the section has led to more than 8 best paper awards at major international conferences (IEEE FG, ICRA, ISMAR, MICCAI, SensorComm) and attracted four Marie Curie fellows. The group has pursued a successful strategy of growth in several key areas: In **vision,** *Davison* was awarded an ERC starting grant. Significant achievements include novel modelling and filtering approaches for SLAM and real-time dense scene mapping. In **intelligent behaviour understanding**, *Pantic* was also awarded an ERC starting grant. This helped to attract an Imperial JRF (*Zafeiriou,* now lecturer) and led to: novel approaches to facial action and emotion prediction as well as novel approaches to robust face alignment, tracking and expression recognition. The group's highly successful research in **biomedical imaging & sensing** is underpinned two EPSRC programme grants (*Rueckert*, *Yang*) and has led to a recent ERC synergy grant for *Rueckert*. This success has allowed a significant expansion in the area of biomedical image computing (*Glocker* and *Lee*). Finally, the area of **graphics** has been revitalized with the recruitment of *Ghosh* whose novel methodologies for modelling the reflectance of materials have had significant impact; for example they have been used for creating digital faces in the movie Avatar (won Best Visual Effects Academy Award).

c. People, including:

c. I. Staff strategy and staff development

Academic Staff

The ethos of the Department is the pursuit of excellence. We encourage ambition and reward achievement. This is realised by recruiting outstanding academics with leadership potential, nurturing junior academics to maturity and supporting all academics so that they can achieve their ambitions, while ensuring that we meet our strategic research objectives.

Our recruitment process aims to attract the best researchers, in line with the Department's strategic objectives. When advertising posts, the Department encourages excellent researchers, usually from any area of Computing. Our international reputation helps to attract an international profile of applicants (*Cadar* from Stanford, *Ghosh* from USC, *Parpas* from MIT, *Przulj* from UC Irvine, *Schuller* from TU Munich). Our research sections actively solicit applications from those with the potential to become future leaders in their research communities. All academics are invited to review the applications and contribute to the selection process. An appointments committee, which includes elected representation, creates the final short list. Candidates are invited for interview and spend at least a day in the Department where they give an open seminar, have individual sessions with potential colleagues and with students, as well as a formal interview. All academics are invited to attend the seminars and add to the feedback from the one-to-one sessions. In order to sustain research in the longer term, the emphasis has been on recruiting junior staff, with the potential to become future research leaders. We are able to offer competitive salaries, help with London

housing and good start-up packages. Eleven lecturers and one senior lecturer have been appointed, including joint appointments with Bioengineering and the Hamlyn Centre.

New staff select an appropriate section to join and are allocated start-up research funds of up to £125k which can cover seed funding for research equipment, travel, DTA funds and additional PhD financial support. In addition, to facilitate settling into our research environment in the first two years, they have reduced teaching duties and no administrative duties. All new staff have a trained Academic Advisor, who provides mentoring, observes occasional lectures, and represents them at the three annual probationary reviews. New academics attend training courses in Teaching and Learning for Engineers, PhD Supervision and Personal Tutoring and are offered courses in research project management. All staff are assisted in proposal writing by the Director/Deputy Director of Research and senior academics. As a measure of the success of our support and acclimatisation process, all new academics have obtained grant funding as PI within two years of their appointments and all who have completed their probationary period have been promoted (*Bradley, Cadar, Kuhn, Pattinson, Pietzuch, Przulj)*.

After probation the Department continues to assist our academics in building their careers. Currently 20% of grant overheads is allocated back to successful grant holders to encourage the accumulation of personal research funds to help with expenses such as seed funding for new initiatives and bridge funding for researchers. The Department meets recruitment, tuition and redundancy costs for researchers.

All staff have an annual appraisal with the Head of Section or optionally the Head of Department where they discuss their current activities, propose future development plans, and raise any concerns. A consolidated report goes to the Head of Department. In the past, this has led to improvements to conditions for individual staff and changes in policy, such as administration restructuring to improve research support.

The Department encourages and supports staff in winning personal research fellowships and major research awards. In addition to help with proposal preparation, senior staff conduct mock interviews (over 25, including 5 at faculty level) for relevant grant or fellowship applications. The College offers one to one coaching and there have been 25 of these sessions. Since 2008 13 major Fellowships (ERC, EPSRC Early Career, Career Acceleration and Leadership Awards) and 5 Junior Research Fellowships have been awarded. We operate a sabbatical scheme in which established staff are encouraged to spend time at other institutions to focus on research.

We have reviewed and rationalised all our support functions to reduce the time spent by academics on administrative and technical tasks. In particular, we have embraced Imperial's new Teaching Fellow structure to hire six Teaching Fellows to perform much of the teaching administration usually associated with academics and to help preserve low average teaching loads (currently 1.5 courses per academic). Academics with very substantial research groups have a reduced teaching load (currently *Gardner, Guo, Muggleton, Pantic, Rueckert, Yoshida, Yang*).

The Department meets as a community for weekly well-attended "Wednesday lunches", termly staff meetings and an annual away day. The Wednesday lunch is open to all academic staff and is a forum for academics to present current research ideas, leading to collaborations across sections. The annual away days have been used to assimilate new academics and update all in one or more of the Department's research themes. The spirit of cooperation engendered by these meetings has enabled the Department to react quickly to ad-hoc research opportunities. We also discuss departmental strategy and both the ideas for administrative rationalisation and the decision to have Teaching Fellows were initiated from these discussions.

Staff are promoted according to merit in an annual promotion round and there are no quotas. As a measure of our progress, there were 23 promotions (7 to Professor) out of 50 returned academics. Another indication of success is retention. Despite an atmosphere of intense recruitment between British institutions, only one academic (*Colton* to Goldsmiths) left for another British institution.

Researchers

The College has fully implemented the Concordat and has achieved an HR Excellence in Research Badge from the EU. For Research staff, Imperial's Postdoctoral Development Centre (PDC) provides skills and career development training, a personal development programme

designed for women and a range of individual support, including coaching and mock interviews – Computing staff attended 38 courses during the REF assessment period. The PDC runs a bespoke development scheme for holders of Imperial's JRFs, publishes a range of guides on postdoc issues and hosts the multidisciplinary Postdoc Reps Network. In 2008, the work of the PDC was acknowledged by winning "Outstanding Support for Early Career Researchers" at the Times Higher Education Awards.

We support our fellows and postdocs in their career development, helping them to secure funding and ensuring they travel and engage with their research community. In addition, we attract many speakers (see our home page) who the researchers are encouraged to interact with. The RA mentor (*Muggleton*) is available to all postdocs for one-to-one career advice and general guidance. The elected representatives run Thursday lunches, and liaise with academics, including with the HoD, and the PDC. We encourage the best Postdocs to apply for fellowships including the highly-competitive, Imperial JRFs and have been awarded five (*Alrajeh, Casale, Costa, Wieseman and Zafeiriou*). Three of these fellows have joined us as lecturers (*Casale, Maffeis* and *Zafeiriou*).

Equality and Diversity

Imperial College's HR policies provide a framework for achieving our aims of supporting equality and the Equality and Diversity Unit's remit includes advice on best practice. We have an institutional Athena SWAN Silver award; the Department has a Bronze award and is in the process of applying for Silver. The College has systematic, transparent and fair hiring procedures (including membership of Stonewall's Diversity Champions Programme and accreditation by Two Ticks), conducts staff questionnaires to help identify problems (with appropriate follow-up procedures), has family-friendly policies whereby meetings and teaching duties are scheduled with parental duties in mind and an associated child nursery. Maternity returners get an Elsie Widdowson Fellowship providing a year to focus exclusively on research; we have had one fellow; there is provision for a generous and flexible paternity leave (four academics took such leave), childcare vouchers and Imperial's subsidised nursery and play schemes (five academics availed themselves of this facility).

Our Department is and is seen to be fair and open to all, resulting in a diverse international department in terms of gender, race, religion and age. Our twelve women academics (23% of academics) include six at Chair level as well as the Head of Department. Our academics were born in over 20 different countries on five continents, with the professoriate coming from 12 countries.

c. II. Research students

We receive about 250 applications yearly from qualified candidates, and recruit between 40 and 50 PhD students each year. Students submit a research statement, which serves to alert potential supervisors, who interview before a place can be offered. Upon joining us, PhD students attend an induction meeting where they meet members of the PhD team, consisting of the Director of Postgraduate Studies (*Drossopoulou*), Admissions Tutor (*Shanahan*), Postgraduate Tutor (*Sergot*), Cohort Mentors (*Pietzuch, Donaldson, Hodkinson*) and Administrator (*El-Kholy*). Each student is provided with dedicated office accommodation, a new high-end computer and appropriate laboratory access. Students are given a budget of £3000 for travel and books. Research groups often provide additional funding for resources, access to grant-funded specialised equipment, and travel. Where possible, researchers in the same research group are co-located.

We have introduced comprehensive monitoring and progress reviewing procedures, compliant with College requirements, to ensure students complete within 4 years. There is an informal review at three months and a formal review after nine months, where the student presents a literature survey and thesis outline. The supervisor, second supervisor and an independent assessor decide whether or not the PhD should continue. At the end of the second year the same assessment team evaluates the status of the thesis plan: what work has been completed, what remains to be done, and whether the research is suitable for a PhD or should be submitted for an MPhil. A draft dissertation is evaluated at the start of the fourth year. The Postgraduate Tutor with the Director of Postgraduate Studies monitors the progress of all research students quarterly and issues are reported to the departmental Executive Committee.

The Graduate School provides skills training courses, and students are required to take at least four. There are a wide range of courses, the most popular of which are Research Management, Personal Effectiveness, Communication and Presentation, Networking, Team-working and Career Management. The Graduate School promotes inter-disciplinarity, facilitating communication between students from different departments by hosting events, including research symposia, poster competitions and lectures by prominent figures from the international research community.

We offer our own training courses which have been approved to meet the Graduate School requirements: a journal reading course, a three day workshop covering practical video and radio interviewing skills and a two-day workshop on science communication, in which students write short press releases about their own research. Other key departmental activities include panel sessions on how to pursue an academic career, an ACM student chapter, 'One Minute Madness' – where each member of a cohort has a minute to present their research, Google-sponsored poster competitions and an annual Imperial College Computing Student International Workshop (http://iccsw.doc.ic.ac.uk/) open to all Computing PhD students, not just Imperial students, organised and run by our PhD students. This allows students to acquire professional skills such as reviewing and conference management. We pay for "Friday cakes" to motivate a student-run seminar series and to facilitate social interaction. PhD students are helped and encouraged to apply for internships and scholarships which are advertised on our website.

The Department has increased the average number of PhD students entering from about 35 in the 2008 RAE period to about 45 students per year by providing funding for 85% of our students via a number of mechanisms: EPSRC awards, departmental scholarships, paying fees for researchers registered as students, highly-competitive scholarships from industry and College. We have established Teaching Scholarships which enables students to pursue a PhD over a period of 4.5 years while gaining experience in teaching and obtaining a teaching certificate. Our approach has led to a 36% increase in the student population from 115 (7/2007) to 157 (7/2013). A CDT in High Performance Computing starting in 2014 supports the sustainability of our PhD programme.

Not only has the intake increased, but so has the success rate. 75% submit within four years, and 85% submit within 51 months, compared with the last RAE period in which 68% submitted on time and 74% submitted within 60 months. Submission has always led to a PhD. The number of PhDs awarded has nearly doubled from 17 per annum in the RAE period to 33 per annum during REF.

d. Income, infrastructure and facilities

d. I. Income

Our strategy has been to target large projects (>£1M), long-term projects (5 year) and prestigious grants. Since 2008, we secured 35 such awards: six EPSRC Programme Grants with substantial involvement from our Department (*Davison & Kelly*, *Gardner x 2*, *Rueckert*, *Yang*, *Yoshida*), two EPSRC Platform Grants (*Luk, Kelly*), eight large EPSRC grants (*Colton, Rueckert*, *Pantic, Lomuscio, Hankin, Yang x 2, Yoshida*), five ERC Starting Grants (*Davison, Pantic, Uchitel, Przulj, Schuller*), one ERC Synergy grant (*Rueckert*), leadership of three EU projects (*Donaldson, Guo, Wolf*), three other large FP7 projects (*Pantic x 2, Rueckert*), two large industrial grants (*McCann - Intel, NEC*), four Wellcome Trust grants (*Rueckert, Yang x 3*), and an RAEng/Syngenta Research Chair *(Muggleton).* The table below shows the number of large-scale grants awarded each year – a total of 35 in the REF period compared with a total of 7 in the RAE period.

RAE 2002-2007	2008	2009	2010	2011	2012	2013
7	6	2	5	2	9	11

Large grants obtained during the REF period versus the RAE period

Diversifying our large-scale research sources has strengthened the vitality and sustainability of our research portfolio. This can be seen in Figure 2(a), which shows that an increasing amount of our research income (spend) comes from EU and charitable sources. The research income from EU and Charity rose from 20% to 31% and 3% to 10%, respectively. Furthermore, the overall research income has also significantly increased during the REF period compared to the RAE period: rising from £5M per annum (£95K per FTE) to over £10M per annum (£200K per FTE). This equates to approximately £1M per academic over the REF period.

Figure 2(b) shows research grants awarded by source. The total value of the research grants awarded during the REF period has increased by more than 180%, as has the RCUK contribution to this funding. Again, the diversification of our research funding has seen new EU funding grow by more than 400%. Industry and Charity funding has also more than doubled. Although RCUK grant spend dropped in 2012/13 compared to earlier in the REF period, the number of new RCUK awards has substantially increased – £10.9M in 2013 compared with £4M in 2011. Most of the spend on these recent grants will occur after the REF period. Sustainability is indicated by the future income already secured, totalling £12.75M, £10.45M, and £6.15M for 2013/14, 2014/15 and 2015/16 respectively.

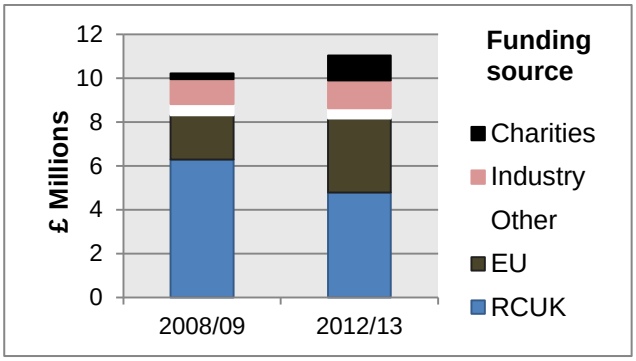


Figure 2: (a) Research income spent according to funding source in 2008/09 and 2012/13

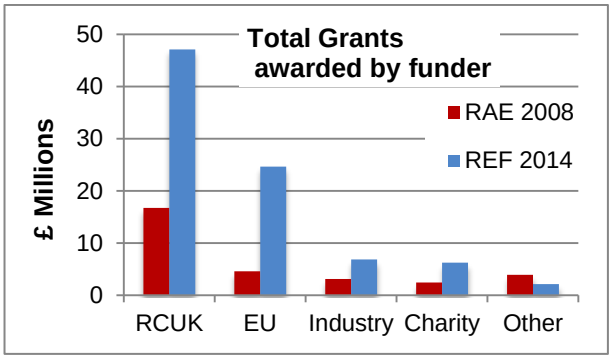


Figure 2 (b) Total research grants awarded during the RAE and REF periods.

While focusing on large grants, we encourage grant proposals of all sizes: several of our successful large projects have grown out of pump-priming grants offered by the Faculty to promote cross-disciplinary interaction (*McCann – led to NEC Centre, Pietzuch and Toni* – led to substantial EPSRC grants). Several of our current research collaborations have come out of earlier consultancy arrangements (*Casale* with SAP, *Davison* with Dyson, *Lomuscio* with BAE). Special events, such as one day Faculty or Department workshops in areas such as Cyber Security, Engineering the Digital Economy, Robotics and Autonomous Systems, Oncology, and Medical Informatics, have also helped to foster collaboration and generate research ideas. Out of the 50 Category A submitted staff, 44 have been Investigators on at least one grant, with 36 as PI.

d. II. Infrastructure and facilities

Imperial College has a transparent funding model where departments receive all the money they earn from teaching and research, and contribute pro-rata costs for running the College. This model facilitates the accurate estimation of future income and helps us to perform long-term resource planning. We have exploited this to ensure that academic staff are well supported and advised, both in obtaining grants as well as in conducting the research itself. In addition, special College and Faculty funding initiatives, events, and the computing and general infrastructure are all crucial in helping researchers to achieve and to make the best of their potential.

The focus on large-scale grants necessitated improvements to our research administration. To supplement the Faculty's research team, we have re-organised our departmental administration team so that each academic has a named individual to assist with the preparation of proposals and management of projects. We have also increased the number of Department finance officers from one to three. Experienced senior academics are routinely asked to mentor, review and advise on proposals and to conduct mock interviews. These changes have helped academic staff to focus on the scientific aspects of their proposals, rather than on administration. During the years 2012 and 2013, over 60% of the 23 submitted proposals of >£1M were successful.

A significant discretionary expenditure is for our Computing Support Group, which we have had since the inception of the Department. We have re-organised CSG, outsourcing standard infrastructure IT to the College services, thus releasing four posts (out of ten) to provide more specialised support. For instance, we recently invested £300K in the initial hardware purchase of a departmental cloud service and used one of these posts to employ a cloud manager. This service is in use by a number of research groups (*Muggleton, Parpas, Rueckert* etc.) requiring large-scale data storage and computation intensive facilities. In addition to the cloud hardware purchase, the

Department has spent a total of £1.1M on general servers and infrastructure and taken advantage of the College provision of the Imperial HPC facility, desktop machines and networking services.

The number of Researchers increased by 79% from 67 in 2007 to 120 in 2013. To ensure that our physical environment met our developing needs, increasing both the quantity and the quality our research space has been crucial. In 2007, the Department had 1687 m^2 classified as research space. Since 2008, we have spent over £600K on refurbishing this space. In 2009, through a £2M Wolfson grant, the new Hamlyn Centre for Medical Robotics added 550m^2 of specialised robotic and imaging facilities. In addition, we have re-purposed a further 285m^2 of our existing estate to dedicated research space, raising our total research space by almost 50% to 2500 m^2.

e. Collaboration and contribution to the discipline or research base

e. I. Nature and scope of research collaborations

The Department has a large number of strategic and opportunistic collaborations. Our academic staff collaborate extensively with other departments and divisions of Imperial (for instance, see **b.I)**. Where appropriate, this is supported by strategically placed joint appointments of academics with other Institutes and departments within Imperial College such as the Hamlyn Centre (*Lee* and *Yang*), Surgery (*Lo*), the Institute for Security Science and Technology (*Hankin* and *Lupu*), Bioengineering (*Faisal* – returned with Bioengineering), Mathematics (*Ham* – returned with Mathematics) and Electrical & Electronic Engineering (*Leung* – returned with EEE).

Our collaboration and engagement with academia, industry and government also extends to the national and international level. Our EPSRC Leadership Fellowship (*Lomuscio*) involves collaborations with both industry and other academic institutions; our Royal Academy fellowships are co-funded by Microsoft (*Gardner, Muggleton*) and Syngenta (*Muggleton*). The six EPSRC Programme Grants we participate in by their nature are multi-institutional and involve industrial collaboration: we are partners on these grants with Cambridge, Edinburgh, Glasgow, KCL, QMUL and UCL, and many companies (including Amazon, ARM, BAE, Redhat). We have numerous collaborations with Microsoft Research (*Cadar*, *Davison, Donaldson, Drossopoulou, Eisenbach, Gardner, Glocker, Lupu, Maffeis, Rueckert, Zafeiriou*). Our EU grants involve European academic and industrial partners. For example, in the eTRIKS project *Guo* leads an academic/industrial partnership (value €23.7M) involving companies such as Roche, AstraZeneca, Sanofi, Pfizer, Merck, Lundbeck, Janssen, GSK, Lilly and Bayer. In the FP7 project CARP *Donaldson* leads a collaboration of 8 academic and industrial partners to develop correct and efficient accelerator programming techniques. In the FP7 project SSPNET *Pantic* leads a European network of excellence of 11 partners in social signal processing. Other EU projects coordinated by us include ARGUGRID (*Toni*) with 5 partners, and HARNESS (*Wolf*) with 6 partners. We also have strong ties with researchers in the United States, such as those at with Stanford University (*Cadar, Luk, Mercer*), MIT (*Parpas, Rustem*) Princeton (*Luk, Rustem*), Mozilla and Google (*Gardner, Maffeis*) and with IBM in the UK and US (*Lupu, Russo, Sloman, Wolf*), who are involved in the UK/US ITA initiative funded by MoD/US Army. Through MOUs and different Royal Society and Royal Academy of Engineering international project schemes we also have strong links to several leading groups in China (*Guo, Luk, Wolf, Yang*) and Japan (*Kramer, Muggleton, Rueckert, Russo*).

A recent example of collaborative leadership is the Cyber Security Institute (established 2013, Director: *Gardner*) funded by GCHQ and EPSRC. Hosted in the Department it has involvement from QMUL, Edinburgh, UCL, Kent and Manchester. The aim is to provide confidence that software will behave in a secure fashion when installed on operational networks.

Collaboration with industry is carried out in our joint research centres. These formulate challenging and relevant research agendas that in turn influence our research strategy. One such example is the Syngenta Innovation Centre (*Muggleton*) that aims to address biological research challenges of the main business sectors (seeds and crop protection) by applying predictive models developed in the Department to empirical data provided by Syngenta. Other examples are the Imperial/UCL Intel Collaborative Research Institute for Sustainable Connected Cities (*McCann*) and the NEC Smart Water Lab (*McCann*). The Intel Institute aims to address the social, economic, and environmental challenges of city life with computing technology, helping to provide practical solutions to problems ranging from droughts and long commute times to wasteful use of energy, whereas the NEC

project develops technologies to improve ageing water supply infrastructures. Joint research centres with Dyson (*Davison*) and Huawei (*Guo*) are currently being created.

Staff are made aware of specific opportunities as they arise. Membership of advisory groups for both the EPSRC and EC (*Hankin, Yang*) has helped this information flow. Wednesday lunches and email are used to describe opportunities of widespread interest.

e. II. Academic leadership and contributions to the discipline or research base

The Department of Computing provides academic leadership at the national and international level, influencing and driving research agendas and strategy.

Esteem and leadership

Leadership evidence based on esteem includes five fellows of the Royal Academy of Engineering (*Kramer, Luk, Muggleton, Sloman, Yang*); five IEEE Fellows (*Luk, Pantic, Sloman, Wolf, Yang*); two ACM Fellows (*Kramer, Wolf*); 15 Fellows of the BCS; five Fellows of the IET and 19 Members of the EPSRC College. Evidence of leadership in research strategy includes Vice President of the ACM (*Wolf*) and membership of the Executive Committee of the ACM Council (*Wolf*) and ACM SIGPLAN Executive (*Eisenbach*); Operations Manager of the IEEE Technical Communities Board (*Casale*); Chair of UKCRC (*Hankin* from 2010-12), UKCRC Executive Committee (*Hankin, Sloman)* from 2010-13); EPSRC Healthcare SAT (*Yang*); and Chair of the BCS Lovelace & Needham Awards Committee (*Gardner* from 2013-16).

Our academic leadership has been recognised by external bodies with prestigious awards including: the ACM SIGSOFT Distinguished Service Award (*Kramer,* 2011, *Wolf,* 2012, Microsoft Software Engineering Innovation Foundation Award (*Uchitel*, 2010), IEEE Engineering In Medicine and Biology Distinguished Lecturer (*Yang*, 2012) and the Roger Needham Award (*Pantic*, 2011).

Contributions to the discipline

Academic leadership at the strategic level is reflected in holding the post of Editor in Chief of International Journals. Examples include ACM Computing Surveys (*Hankin,* 2007-13), IEEE Transactions of Software Engineering (*Kramer*, 2006-09), ACM Transactions on Reconfigurable Technology and Systems (*Luk*, 2008-13), IET Software Journal (*Russo*, 2006-13), Image and Vision Computing (*Pantic*, since 2008) and IEEE Transactions on Network and Service Management (*Sloman* since 2011). Our academic staff also account for more than 40 Associate Editor/Editorial Board memberships, and guest editor for many international journal issues.

Our academics serve on numerous international advisory boards, including President of the INRIA Scientific Council (*Hankin* from 2011-15), Membership of the EU FET Flagship External Advisory Group (*Hankin*); INRIA Int. Network Research Evaluation Panel (*Sloman*); INESC Lisbon (*Sloman*); National Institute for Informatics Tokyo (*Kramer*), Chair LERO Review Panel for Science Foundation Ireland (*Kramer*), Convenor Hong Kong Computer Science/IT Panel RAE 2014 (*Kramer*), ANVUR VQR (2004-2010) REF-like Panel in Italy (*Yoshida*), Chair Vienna Science & Technology Fund (*Wolf*), Chair WHO Technology for Patient Safety Panel (*Yang*), Chair of the Academic Committee BME Shanghai Jiao Tong University (*Yang*).

Academic leadership is also effectively measured by our service to conferences. Each academic is typically a committee member of 2-5 international conferences per year. Leadership also includes:

- **Keynotes** - Our academics gave about 150 Keynotes. Examples include *Cadar* at ESSoS'12, Edalat at CCA'11, *Gardner* at DBPL'09, Hankin at TTI Vanguard Cybersecurity 2010, K*elly* at FHPC'13, *Kramer* at ICSE'12 and at APSEC'12, Luk at FPL'10, at FPT'11, *Muggleton* at ICML'10, at ECAI'12, *Rueckert* at MIUA'11, *Schuller* at ICCE'13, *Shanahan* at AISB'13, *Sloman* at NOMS'12, *Yang* at MICCAI'10 and at ERUS'12, and *Yoshida* at TGC'13.
- **Conference chairs** - Our staff also serve as Program or General Chair (GC) for approximately 35 Conferences and Workshops. Examples include *Drossopoulou* for ESOP'08 and ECOOP'09, *Gardner* for ESOP'13, *Huth* for QEST'09 and TRUST 2013 (GC), *Lomuscio* for AAMAS'14, *Lupu* for CNSM'11, *McCann* for SASO'11, *Pietzuch* for DEBS'13 and DAIS'14, *Schuller* (GC) ICME'14, *Casale* (GC) and *Field* for ICPE'13, *Field* (GC) and *Knottenbelt* for MASCOTS'09, *Kramer* (GC) and *Uchitel* for ICSE'10, *Harrison* (GC) and *Casale* for SIGMETRICS'12, and *Yang* (GC) and *Rueckert* for MICCAI'09.