Institution: University of Bristol

Unit of Assessment: 11-Computer Science and Informatics

a. Overview:

The Faculty of Engineering at the University of Bristol (UoB) is a thriving, collegiate and successful unit which is recognised for its innovative research and knowledge transfer. Key highlights of the Computer Science submission for UoB include research on the application of computer games to psychological clinical interventions [**Coyle-1,2**], magnetostatic active contour models [**Mirmehdi-1**], quantum Merlin-Arthur proof systems [**Montanaro-1,3**], and Fully Homomorphic Encryption (FHE) [**Smart-4**]. These academic highlights, combined with impact through spin-outs [see **REF3b: XMOS**], four ERC fellowships (including two Advanced ERC grants), external recognition (Bull and Fraser elected fellows of the IEEE and Royal Society of Arts, respectively and Flach appointed as Editor-in-Chief of the Machine Learning Journal), contribute to this return for the Computer Science submission at UoB being significantly advanced compared to its position in RAE2008. In RAE2008, the Computer Science submission detailed research spend of around £38k per FTE per year; in the REF2014 period this now exceeds £65k per FTE per year. This enhanced performance will be sustained into the future by the current grant of portfolio £14M for the forward order book.

A hallmark of the Faculty is the strong collaborations, both across various disciplines (within the University and internationally) and across the academic/industrial divide. This multi-faceted and broad approach to research resulted in the Faculty reorganising its internal processes and structures in 2009-10, from six departments to a parallel structure of teaching and research across the Faculty. Research activities are now organised into 18 Research Groups, with established foci and critical mass. Each Research Group was identified based on academic strengths and alignment with key strategic priority areas. Five of these Research Groups fall within REF2014 Unit of Assessment (UoA) 11, with staff associated with four different teaching departments (Computer Science, Electrical & Electronic Engineering, Engineering Mathematics, and Civil Engineering (Systems Centre). The research groupings, whilst similar to RAE2008, are not directly comparable. Detailed listings of academics and their associated Research Groups are provided in **REF1**.

Our five groups are introduced as follows. **(1) The Cryptography Group (CG)** conducts research into Cyber Security focusing mainly on cryptography. Its broad remit, ranging from highly theoretical blue skies activities (e.g. FHE) through to highly applied areas (e.g. side channel analysis). **(2) The Intelligent Systems Laboratory (ISL)** has ongoing research activities including foundational work in machine learning, data mining, algorithms and uncertainty modelling, with applications to web intelligence, machine translation, bioinformatics, semantic image analysis, robotics, and natural intelligent systems. **(3) The Bristol Interaction and Graphics Group (BIG)** focuses its research around participatory design and deployment in real-world settings of new technology, in order to understand the relevance and viability of prototypes, and to seek new inspirations from everyday settings. **(4) The Microelectronics Group (MG)** researches the fundamental underpinnings required for future computer systems spanning the mobile/embedded and high performance computing spaces. Specific research directions include parallel and reconfigurable computer architectures, energy efficient computing, fault tolerant systems, design verification, and next generation technologies, such as 3-D chip design and NEMS. **(5) The Visual Information Laboratory (VIL)** conducts its research primarily in the areas of video communications, 3-D visual mapping and navigation, medical imaging, animal biometrics and image-sensor processing.

b. Research strategy

Due to the diversity of our research portfolio, strategy is defined at the Research Group level.

Cryptography Group: CG is unique amongst international cryptographic groups in that it combines theoretical and practical insights into all of its research directions; this results in demand from leading international academic and industrial groups for collaboration. For example, in the REF period, papers have been published with authors from ENS Cachan, ENS Paris, Georgia Inst. of Tech., Hewlett-Packard Laboratories, IBM TJ Watson, IBM Zurich, K.U. Leuven, Portland State University, T.U. Darmstadt, U.C. Louvain, U. Aarhus, and U. Catania. The Group's strong links to

the main industrial and academic groups in Europe, are also due to the pivotal role it played in co-organizing the ECRYPT and ECRYPT-II Networks of Excellence funded by the European Union. The Group's reputation formed the basis of UoB being awarded Academic Centre of Excellence in Cyber Security Research status in an EPSRC/GCHQ exercise in 2012.

Cryptography spans highly applied work such as implementation aspects (Page), attacks based on side-channels (Oswald), and general security (Tryfonas), through to more traditionally theoretical aspects such as protocol design and analysis (Warinschi), symmetric cryptosystem and hash function construction (Stam), and mechanism design [**Smart-3**]. The broad remit of the Group means that both theoretical and practical activities co-exist in a manner not seen elsewhere. Three illustrative examples are:

- Theoretical analysis has been applied, and will continue to apply to important real world protocols such as SSL/TLS [**Page-3**, **Smart-3, Stam-4**], the Trusted Computing Group's DAA protocol [**Page-2**], HSM APIs [**Warinschi-2**], the EMV chip-and-pin protocol, SSH, Helios [**Warinschi-4**] and IPSec [**REF3b:CRYPTO**].
- CG's theoretical protocol development is always accompanied by experimental implementation, with designs evolving symbiotically with their security and efficiency evaluation. This approach has resulted in CG's protocols being included in the IEEE 1363.3 standard [**Smart-1**], and in groundbreaking implementations of FHE and MPC technology [**Smart-2,4**].
- CG's recent results [**Oswald 1-3**] on side-channel analysis have focused on obtaining a sound statistical basis for many of the current techniques used, which had previously only been understood informally. This mathematical analysis is now being applied to develop sound testing strategies for commercial testing laboratories.

Intelligent Systems Laboratory: ISL models "intelligence" both in natural and artificial systems by combining different disciplines (e.g. neuroscience, machine learning, multi-agent systems), diverse philosophies (e.g. Bayesian methods, fuzzy systems) with wide-ranging applications (e.g. bioinformatics, social modelling, flood forecasting, healthcare and robotics). This multi-faceted approach is then funnelled into three main areas of activity: large-scale data mining (big-data); intelligence in biological systems; and adaptive autonomous agents.

Large-scale data mining concerns the scalability of machine learning and data mining algorithms to model the large and complex data sets generated by social networks, internet and large scale media **[Cristianin-2,4]** and also by systems biology and bioinformatics applications (Campbell (ICG), Cristianini, De Bie**,** Gough, and Ray). These challenges often require the design and implementation of novel algorithms, such as for network inference [**Gregory-1,2**], or for structured data [**Flach-2**], as well as new theories of algorithm design exploiting advanced optimization techniques (Clifford) and [**De Bie 1-4**], and quantum computing (Montanaro). In this context, the comparison and calibration of algorithms is also a key challenge motivating generalisations of techniques such as ROC analysis [**Flach-3,4**]. The practical application of big-data algorithms involves a significant systems-level challenge in terms of real-time data collection, processing and pattern analysis on an ultra-large scale. This challenge is being addressed by ongoing work in the areas of genomics [**Gough-1**], and network threat analysis [**Kovacs-2**, **Martin-3**].

Intelligence in biological systems concerns computational neuroscience and biologically-inspired algorithms. Here, the focus is on understanding the type and efficacy of algorithms implemented by biological systems and on exploiting this understanding to develop novel approaches to artificial intelligence. For example, in neuroscience there are fundamental questions concerning the possibility that the brain is running certain statistically optimal decision-making algorithms and on the structure and properties of spike trains used for information propagation and processing [**Houghton-1,3**]. From a different perspective, social insect behaviour provides the inspiration for new collective decision-making algorithms [**Kovacs-1**] and biology also inspires certain genetics-based machine learning methods [**Cliff-2**, **Kovacs-2**].

There is a significant research effort in ISL towards the development of *adaptive autonomous agents* as software entities [**Kovacs-2,3**] and also as robotic systems. In this area, there is ongoing

activity both in the design of individual agents, and in complex multi-agent systems where the focus is on emergent properties and behaviours. For the former, non-Boolean models of concepts and ontologies have been developed and applied [**Lawry-2,3**, **Martin 2-4**], whilst for the latter, research has concentrated on the systemic effects of automated algorithmic trader agents in the global financial markets (Cliff), and ongoing research into agent communications in terms of multiagent dialogues and consensus modelling (Cliff) and [**Lawry-4**]. Much of this research falls within the scope of the EPSRC-funded initiative into Large Scale Complex IT Systems (Cliff) and also overlaps with Bristol's EPSRC doctoral training centre in complexity science (BCCS). There is a growing interest in fundamental issues concerning the nature of autonomy for intelligent systems deployed in evolving environments where they must adapt to new and unexpected scenarios; e.g. involvement in the EPSRC-funded RIVERAS project into methods for verifying of autonomous systems, [**Lawry-3**] and Cliff's work on managing cloud computing infrastructures [**Cliff-4**].

Bristol Interaction and Graphics Group: BIG has an unusual approach to HCI in UK based groups as it aims to conduct research by combining engagement in real-world settings with the design of novel interactive physical computing systems. This unique approach has led to successful collaborations, evidenced by co-authored papers, with the following companies Autodesk, Hewlett-Packard, Nokia and Philips, as well as universities such as DFKI [**Fraser-3**], Eindhoven, Osaka, Tohoku and Toronto. The Group has received significant contributions of equipment from Nvidia and Texas Instruments; and funding from Microsoft and Thales. In addition, Subramanian has held visiting professorships at both Gothenburg and Tohoku in the REF period.

The Group has two key modi operandi. The first, is to create innovative interactive input and output technologies through physical, electro-mechanical and computational techniques (Fraser and Subramanian). Activities include technologies as diverse as large screen and tabletop displays with multitouch and "multi-view" optical forking capabilities, mobile steerable projections, "multi-feel" systems using ultrasound that provide multi-point mid-air haptic feedback, enhanced mobile 3-D scanning for gesture recognition, and brain-computer interfaces to detect confusion. This work, using the approaches described in REF3a, is expected to form the basis of a future impact case study. The second major thrust concerns the understanding and evaluation of applications for these designs in real-world settings to inspire new interaction theories and novel evaluation metrics. For example, exploring cognitive ability through techniques to measure and enhance spatial skills [**Fraser-1**, **Cater-1,2**], producing novel metrics for judging agency and control over novel input techniques. Aligned with this thrust is novel use of computer games for clinical interventions in psychology [**Coyle-1,2**], and understanding the limit of competitive gamification in motivating users [**Preist-2**].

Microelectronics Group: MG focuses its research around the challenge of many core architectures. For example, McIntosh-Smith's cloud based GPU work, Eder, Hollis, and May's design, verification and uses of the many-core XMOS processor [**REF3b:XMOS**]. The Group collaborates with leading international academic and industrial groups on several different facets of many core architecture research, including: computer architecture, HPC, energy-efficient designs, on-chip and intra-chip communication, verification, fault-tolerance and reliability, and very-large-scale integration technology. Members of the Group have co-authored papers with colleagues in various companies, including Broadcom [**Eder-3,4**], IBM, and XMOS [**Eder-2, May 2-4**]. During the period, the Group has had funded research projects with companies such as ARM, IBM, Intel, Microsoft, Nvidia, STMicroelectronics, and XMOS. Major ongoing research subareas of the Group include power-aware and energy-efficient computing [**Hollis-1**, **McIntoshSmith-2, Nuñez-Yañez-1,4, Pradhan-1, Pamunuwa-1**], fault-tolerant hardware designs and algorithms [**Pradhan-4**], dynamically adaptive techniques and reconfigurable devices [**McIntoshSmith-2**, **Nuñez-Yañez-2**], and advanced integrated circuit designs including extremely energy-efficient 3-D devices and nano-electro-mechanical relays [**Pamunuwa-2,3**].

Visual Information Laboratory: The VIL combines theory and application across visual communications, autonomous systems and pattern recognition. For example, new synthesis-based compression and immersive video analysis draws heavily on knowledge of the human visual system and pattern recognition to provide advances in visual communications. Similarly, tracking and terrain analysis brings together researchers from robotics, psychology, anatomy, and

computer vision. Bristol Vision Institute (BVI) provides a rich and unique collaborative environment for the Group comprising approximately 120 researchers from psychology, biology, anatomy, mathematics, engineering, medicine and the creative arts.

Four key highlights of the Group's work in the REF period have been:

- Robotics and autonomous systems studies have produced novel methods for linking visual cues with dynamically varying environmental conditions. Real-time visual SLAM [**REF3b:SLAM**] (Calway and Mayol-Cuevas) analysis continues to deliver state-of-the-art feature matching, relocalisation, and higher-order mapping, which has underpinned mobile augmented reality applications and on-body vision-based workflow analysis. Having addressed interactions between locomotion, environmental awareness and visual sensing, the aim is now to emulate human and animal vision in providing stable high-speed locomotion over rough terrain.
- Animal biometrics developments have enabled unique automation of unconstrained biological field observations for behavioural and conservational analysis [**Burghardt-1,3**] [**REF3b: VAB**]. The analysis hierarchy, comprising pose estimation, model fitting and extraction of unique phase singularities, is capable of robust animal identification. VIL's animal biometrics technology will also be exploited for secure authentication based on unique crystal patterns, and is the subject of an ongoing patent application.
- Immersive technology research has enabled understanding and characterization of the impact of video acquisition, transmission and display parameters on the content creation and consumption processes. It has delivered compression results which exploit novel texture synthesis instead of conventional transform methods [**Bull-3**]. Rate-Distortion-Optimisation based on Pyramid Vector Quantisation has delivered outstanding HD video quality coupled with dramatic complexity reductions. [**Bull-4**] [**REF3b:ProVision**].
- Finally, healthcare and biosensing have been a key application focus for VIL's detection, classification and tracking analysis, with leading performance in medical image segmentation and classification using active contour models such as CACE and MAC [**Mirmehdi-1,3**]. Related surveillance analysis has delivered leading-edge methods for: mitigating the effects of atmospheric turbulence and haze [**Achim-4**], enhancing low-light imagery, denoising, and fusion [**Achim-1,2, Bull-2**], and understanding brain functionality [**Nuñez-Yañez-2**]. Further applications in healthcare and biosensing are major opportunities for the future: for example, correlating human behaviour and activity with hospital records to assess disease progression and acute conditions will be followed in the major new EPSRC IRC SPHERE.

c. People, including:

i. Staffing strategy and staff development

The allocation of new academic appointments is guided by the strategic direction of the Research Groups, and current understanding of likely future opportunities in the wider research community. For example, the growth in the BIG group has been predicated on the belief that engineering of devices and in-the-field testing should develop hand in hand. Appointments are made with a view to expanding capability in new related directions and to reinforce interdisciplinary opportunities.

Staff are encouraged to apply for available fellowships, with significant success. In the REF period, there have been: two Royal Society Wolfson Research Merit Awards (Cristianini (2007-11) and Smart (2008-2013)); two ERC Advanced Grants (Cristianini and Smart); one ERC Consolidator award (De Bie) and one ERC Starting Grant (Subramanian) award ; two EPSRC Leadership Fellowships (Clifford and Oswald); two RCUK Fellowships (Burghardt and Ray); two Royal Academy of Engineering/Royal Society Industrial Secondments (Eder and Nuñez-Yañez); a James S. McDonnell Scholarship (Houghton) and Martin has held a British Telecom Senior Research Fellowship since 2001.

There are support mechanisms at University, Faculty and School levels that enable all staff to reach their potential. For example, academic staff are supported by the central University by means of one-year University Research Fellowships, awarded through a cross-University competition. These enable staff to spend up to one year concentrating solely on research. Such

Fellowships have recently been awarded to Clifford (2011-12), De Bie (2011-12), Eder (2011-12), Flach (2008-09), Fraser (2009-10), Gough (2011-12), and Smart (2009-10). In addition, there are pump priming funds at both the University and Faculty levels to kickstart new directions in research, and fund proof-of-concept activities.

Our PDRA community is diverse and, at any one time, typically includes representatives from ten or more non-UK countries. Diversity is supported by the Universities commitment to the Concordat to Support the Career Development of Researchers, and the fact Bristol is a founding member of the Royal Society Athena SWAN Charter.

All junior staff (academic and PDRAs) are encouraged to participate in the day-to-day workings of their respective Research Groups; via Group meetings, study groups, PhD reading groups and other activities. Each Group is supported by an enabling budget, and each staff member has access to additional Faculty pump-priming funds for other purposes.

Development of junior researchers (PhDs and PDRAs) is enabled by frequent exchanges with leading international research groups. For example, in the CG this has been done through membership of the ECRYPT and ECRYPT-II (EU funded) and CryptoForma (EPSRC funded) networks. The long-term career aspirations of PDRAs are further fostered by encouraging them to take part in all aspects of University life. All PDRAs are encouraged to develop their own research agendas as well as pursuing the projects on which they are working. This is seen as a vital part of career progression for young researchers who are wishing to make the transition from PDRA to a more permanent academic or industrial role. They are also encouraged to pursue activities which contribute to the wider academic good, and provide enhanced impact for their research.

ii. Research students

From the day of arrival to their graduation, research students are encouraged to form and maintain a strong affiliation to their Research Group, whilst fostering interaction with other Groups and disciplines, where appropriate. Desk allocation and induction activities, for example, are based, first and foremost, around cognate research groupings rather than around broader departmental disciplines. Close attention has been paid to space allocation and layout of offices.

Students meet regularly and frequently with their supervisors, both individually as well as when working as part of research teams that may involve other members of staff and other PhD students. In this way, a balance is achieved between individual supervision as well as teamwork and interaction with a wider research activity, often with colleagues from other departments, universities and from industry.

Day-to-day administrative support for postgraduate students is provided by the Graduate School of Engineering, a Faculty-wide body which provides consistent expert advice and specialized support for all students, and a “one-stop shop” for most practical or administrative student needs. Overall PhD training provision is planned and agreed between student and supervisor. The student is empowered to pursue appropriate training opportunities, with the supervisor and Graduate School bringing such opportunities to the student’s attention. Such opportunities may include dedicated training courses of the University, external summer schools, industrial placements and language courses. The Graduate School is further supported by the newly formed University-wide £650k Bristol Doctoral College, to ensure that good practice is promulgated across the University.

All Research Groups organise a series of seminar programmes with local, national and international speakers. This forum facilitates interaction and discussion between researchers at all levels. All Groups also hold regular reading-group sessions that encourage students to study papers in depth. These may be outside their direct area of expertise, and some Groups also hold weekly student-only study groups, organised by PhD students, to provide extra help in those areas that the students have, themselves, identified as common weaknesses.

Training of students is augmented by additional procedures specific to each Research Group, that reflects different sub-disciplines. For example, in the CG, students are regularly sent to international “Summer Schools” where approximately 100 participants are taught specific techniques by the world’s top researchers. Recent summer schools, with significant numbers of

Bristol students in attendance, have been held in Aarhus, Bochum, Porto and Tel Aviv.

The development of broad or transferable skills is given high priority. All students are required to attend a workshop on "Management of their PhD" during the first few weeks of their study, and a number of short courses are organised to cover subjects such as presentation skills and intellectual property. New postgraduate students who wish to undertake paid teaching are also required to attend a Teaching and Learning Programme which is delivered by the Graduate School of Education on behalf of UoB. In 2012, two PhD students (Rackham and Sardar) were recognized for their "outstanding contribution to the regional STEM programme" by the "STEM department of the Year" award.

The process for carrying out annual reviews of postgraduate research students embodies the key principle of independent review of progress. The main purpose is to assure the student, the supervisor(s), the Research Group, the Department and the Faculty, that academic progress is satisfactory at all stages of the research programme. All PhD students are reviewed, at least once a year, by an independent panel (i.e., a panel containing at least one member of academic staff who is not involved in supervision of the student). The review is an opportunity for students to discuss their research, their supervision and their general training programme, and any other issues they think are relevant to their academic progress and development. The review process requires students to produce a written report and attend an interview and/or give a presentation.

This UoA is involved with four Doctoral Training Centres.

(**1) The CDT in Communications Engineering**, supported by £2.2M of EPSRC investment, combines the strengths of the VIL and the BIG groups with the Electrical Engineering based Centre for Communications Research and world leading mathematics capability within Bristol. With the support of some 25 major UK companies and trade organisations, the total funding for the Centre over eight years approaches £10M.

(2) The Bristol Centre for Complexity Sciences delivers unique interdisciplinary Doctoral Training focusing on the applications of mathematical and computational techniques to understanding of the complex systems studied in different areas of Science and Engineering. The Doctoral Training centre was funded by EPSRC in 2006 with grant of £4M, and in 2011 the EPSRC has recognized the success of the Centre by renewing it with a grant of further value of £3.6M pounds.

(3) The Bristol/Bath Industrial Doctorate Centre in Systems is an £8M EPSRC investment in stakeholder-driven, multi-methodological research. Since 2007 (setup up initially as the EngD Centre in Systems) it has recruited over 70 Research Engineers on its engineering doctorate programme, and involves over 30 industrial partners sponsoring the researchers. Most projects have a multidisciplinary nature and a good proportion of them are conducted within the primary scope of computer science.

(4) The new **Wellcome Trust DTC in Neural Dynamics** has £3M of investment and will support 23 four-year studentships. The aim of the centre is to train a new generation of neuroscientists able to use both experimental and computational methods to investigate neural systems. Each of the students is jointly co-supervised by a computer scientist or mathematician and by an experimental or clinical neuroscientist. The centre is co-directed by Houghton.

In addition, strong involvement will occur with the newly announced EPSRC CDT in Quantum Engineering at Bristol.

c. Income, infrastructure and facilities

Income: Computer Science at Bristol aims to achieve a diversified pool of funders; ranging from traditional UK funding councils through to EU grants and industrial sponsors. It aims for a balance between Bristol-only projects, and larger-scale multi-institution initiatives. As described in various parts of the REF submission, funding has been obtained from bodies such as EPSRC, ESRC, NERC, the EU (STREPs, IPs and ERC grants), DARPA, MOD, TSB, DSTL, RCUK, in addition to industrial support, both in cash and in kind. Direct comparison with the RAE2008 is difficult due to the introduction of full economic costing and the reorganisation of our research groupings, but in

RAE2008 the Computer Science submission detailed research spend of around £38k per FTE per year, in the REF2014 period this exceeds £65k per FTE per year. Research funding has accelerated in the last couple of years, the forward order book (i.e. total grant income per FTE for active grants proportioned over future years) is CG £498,991, ISL £288,963, BIG £374,087, VIL £284,068 and MG £359,294; making a total of £ 14,078,353 for the forward order book.

Infrastructure: Computing, file storage and internet support is provided for all academic and research staff, visitors and research students on an on-demand basis. This includes multi-terabyte filestores with multiple-copy back-up. Networking consists of a 20Gbit backbone with 1Gbit to desktop and wireless throughout all buildings. Management of the technical infrastructure is carried out by a small team of highly experienced staff. Current projects include high-dynamic-range displays, new interactive walls displays, haptic devices, and a 3-D projection screen.

The UoA provides 100 PCs running the latest version of Centos which can be used for research via a job scheduling system. In addition, there is access for all members of the Faculty to 260 PCs that run Windows 7. In addition, there are two Centos and two Windows servers, and VPN access to allow for secure off-site interactive access. Industrial software like Maya and Modelsim, as well as EDA licenses (e.g. Cadence, Mentor Graphics etc), are available for research. As part of the Cadence licence, UoB is the lead University in the Cadence Academic Network in Europe on “Advanced Verification Methodology”.

All computer facilities are replaced on a five-year cycle. However, computing infrastructure can be reviewed and updated, as necessary, subject to available funds. There is an annual budget of £68,000 allocated to computer equipment. Of this, £28,000 is earmarked for the departmental laboratory upgrades. Combined with software and other IT expenditure, the total non-research grant related IT spend is >£110,000 per annum.

Facilities: The UoB recognises that simulation and modelling capabilities are fundamental tools for enabling world-class research, alongside the traditional theory and experiment of the scientific method. Thus, it has undertaken a strategic investment of significant capital - around £12M since 2006 - into developing a world-class advanced computing facility - the Advanced Computing Research Centre (ACRC). The ACRC includes not only high performance computing, but also data storage and the associated long term data curation, staff and student training in HPC, and critical supporting infrastructure such as high speed networks and advanced energy-efficient data centres.

Internal HPC Facilities: The UoB has leading HPC and research data storage facilities, in terms of competitiveness, capacity, capability and best practice in exploiting maximum return from its investments. Since its creation in 2007, the ACRC has overseen the installation of three large HPC systems. The *BlueCrystal* facility was ranked number 66 in the June 2008 Top500 list; and in 2011 the ACRC constructed a resilient, expandable petascale research-data storage facility, *BluePeta*. This is a multi-site, high resilience, high availability system with over one petabyte of real usable capacity.

The *BlueCrystal* facility is spread over two state-of-the-art data centres which utilise advanced and highly efficient water cooled racking systems. *BlueCrystal* was installed in three separate phases: in 2007 (now, mainly used as a teaching facility); Phase2 was commissioned in 2008 and the Phase3 system upgrade was installed in early 2013, with more than 200 TFLOPS of computing power. This facility, once again, puts the UoB in the top tier of HEI-based HPC facilities.

In Computer Science, this facility has been used by: the CG to investigate lattice security estimations and to develop ground-breaking Fully Homomorphic Encryption technology [**Smart-4**]; by the ISL to analyse correlation between news feeds and financial data to perform machine translation of natural language [**Cristianini-4**], and to analyse genetic markers in genes for cancer research and by the MG to model networks on a chip.

Shared HPC Facilities: The e-Infrastructure South consortium is a partnership of the Universities of Bristol, Oxford, Southampton and UCL. Formed in 2011, the Consortium has the aim of exploring and exploiting opportunities for the co-development and sharing of e-infrastructure capabilities (hardware, applications software, user support services and people and skills) across the founding

institutions and through linkages with other academic and industrial partners across the South of England. In January 2012, EPSRC awarded £3.8M to the consortium to establish the e-Infrastructure South Centre for Innovation. This funding has enabled the consortium to procure shared HPC resources for shared use across its partners and will support further engagement with industry and universities within the region, as well as delivering and advancing the research aims of the consortium partners.

The EPSRC funding has been used to procure two significant (Tier 2) HPC systems hosted on behalf of the Consortium at two technical hubs: *Emerald*, located at the STFC's Rutherford Appleton Laboratory, is a large GPU system utilising 372 NVIDIA Tesla processors. *Emerald* has a sustained capability of 114 TFLOPS and on installation in March 2012 was, by far, the largest GPU system in the UK, and one of the largest such systems in Europe. *Iridis* is a 12,000 core x86 cluster giving a performance of 108 TFLOPS. Iridis provides the workhorse for highly scalable analysis which cannot be accommodated on machines currently available at local consortium sites. Together, the *Emerald* and *Iridis* resources, represent £2.8M of HPC infrastructure that is available to UoB researchers.

These facilities have been used to develop [**McIntoshSmith 1-4**] novel GPU software to perform various scientific calculations, in diverse domains including aerospace, biochemistry, and virus mutation modeling. The goal is to establish the feasibility of utilizing GPU software in a cloud environment.

Group-Specific Facilities: Each Group also maintains a set of tools and facilities which are specific to their research. For example, the CG maintains a small facility for side-channel analysis, as well as for FPGA prototyping. This enables side-channel analysis to be grounded in real-world data; in addition it has a dedicated experimental setup to perform Multi-Party Computation calculations. The ISL maintains a group of dedicated servers for the storage and analysis of news content, including their translation and annotation, as well as an EPSRC-funded stand-alone network for investigating the design and management of automated trading systems, such as those found in the global financial markets. Gough's SUPERFAMILY research facility [**Gough-1**] requires the maintenance of web servers hosting five biological databases accessed approximately once per second by over 10,000 distinct sites per month; the servers perform advanced calculations on behalf of external researchers in biology. BIG has a dedicated laboratory space for design, development and testing of novel interface devices.

The VIL maintains two specialist facilities. Firstly, the BVI Vision & Movement Laboratory (funded by Wellcome) is an interdisciplinary facility for measuring locomotion, head, eye and hand movements, in a wide variety of visual environments. The facility hosts a 12-camera motion capture system, a treadmill with integrated force platform to measure bio-mechanical responses to visual stimulation and a mobile eye tracker. Secondly, the Bristol-BBC Immersive Technology Laboratory (BITL) is a unique BBC/EPSRC funded facility linked to Aardman, Technicolor and Arri. The facility hosts full-time seconded staff from the BBC, and comprises high-speed, high dynamic range and high resolution equipment, both cameras and displays, and a comprehensive professional video editing suite supporting advanced workflows. It also hosts the only immersive measurement suite of its kind with state of the art eyetrackers, physiological and immersion measurement systems, controllable lighting and other subject monitoring equipment.

Mayol-Cuevas is the deputy director of the Bristol Robotics Lab (BRL). The BRL is a 3000m^2 purpose-built facility supporting researchers from UoB and University of West of England to work alongside industrial partners. The laboratory provides shared facilities to underpin cutting-edge robotics design techniques, for example 3-D printing, laser cutting, vacuum casting, two indoor flying areas, motion capture equipment, and a wide range of mechatronic and electronic test and build capabilities. To support individual projects, BRL is a reconfigurable space which allows expansion of project areas suitable for bespoke challenges such as increased height for airborne quad-rotors or clean rooms for environmental and energy-based robotics.

d. Collaboration or contribution to the discipline or research base

As evidenced elsewhere in this document, and in other parts of the submission (e.g. REF2 and

REF3), all Groups are heavily involved in collaboration both with external academic and industrial partners, and with interdisciplinary teams around the globe. These activities are encouraged by funds to enable staff to: attend international conferences and make visits; attend locally organized events and support their Industry Advisory Boards. In this section, three case studies are outlined, showing the depth, extent and effect of major collaborative efforts.

Exemplar of Research Collaboration: Members of the VIL maintain a number of strategic research collaborations, primarily through BVI, established in 2008 by its current Director, Bull. VIL members have built upon BVI's relationships with the life-sciences (biologists, psychologists, ophthalmologists and anatomists), the creative arts (cinematographers, directors) and also with engineers in BRL. Selected collaborative interactions include:

i) The EPSRC SPHERE IRC - a £12M collaboration with Toshiba, IBM, Reading and Southampton Universities addressing the question of how visual analysis can improve point of care monitoring and testing.
ii) A major TSB/EPSRC £1.5M programme, (with partners including the BBC, Toshiba, Mubaloo, & ProVision) creating new interactive visual experiences associated with wildlife imaging and recognition [**Burghardt-1,3, Bull-4**].
iii) An EPSRC grant and a 4M Euro EU Marie Curie ITN building on Bristol's innovative approach to video compression using CG methods in conjunction with static and dynamic texture modelling (with HHI Berlin, Univ. Aachen, Univ. Nantes, Purdue, Technicolor, Microsoft, BBC R&D) [**Bull-3, Agrafiotis-2**].
iv) Contributions in image processing, fusion and denoising [**Achim-2, Canagarajah-2**] delivered as part of the £60M UK MoD Defence Technology Centre in Data and Information Fusion (DIF-DTC) (a partnership between General Dynamics, BT, QinetiQ, and seven academic institutions). The latter spawned a subsequent partnership with DSTL through the EPSRC University Defence Research Centre (UDRC) in which VIL produced the first realisation of scalable video fusion, and with General Dynamics and Cambridge University, where VIL's research on mitigating the effects of atmospheric turbulence on long range surveillance imagery [**Bull-2**] is now being evaluated for commercialisation by GDUK and Roke.
v) Image content analysis [**Canagarajah-1**] was deployed in the MOD Grand Challenges Competition, and is a key part of the EPSRC IU-ATC international project on developing an automatic crop disease diagnosis system to support rural farmers in the UK and India. This is a £10M collaborative project involving five UK Universities, a number of industrial partners and Indian universities.

Exemplars of Interdisciplinary Research: Much of ISL's work takes place in collaboration with colleagues from the life sciences, cell biology and neuroscience to epidemiology, ecology and social insects. Gough's analyses on comparative genomics [**Gough-2**] and biological sequence analysis [**Gough-4**], whilst his SUPERFAMILY database [**Gough-1, Kovacs-4**] is a heavily used online resource for biologists. **Houghton** has focused on the application of computer science to improve data analysis in neuroscience [**Houghton-3,4**]. Work has continued on applying machine learning to breast cancer research [**Campbell (ICG)-1,3**]. Collaboration [**Gregory-4**] with colleagues in social medicine investigated drug addiction and epidemics. Collaboration with colleagues in the Bristol Ant Lab enabled the investigation of a common statistical basis for decision-making in brain neurons for both primates and ants [**Kovacs-1**].

How collaboration Informed Research Activities: CG's computing on encrypted data started in 2008, within the EU funded CACE project (Universities of Aarhus, Bochum, Bar-Ilan and Haifa) [**Smart-2**]. As a result, further work ensued with K.U. Leuven (funded by ECRYPT-II) before leading to a major role in the $20M PROCEED DARPA project. This, in turn, led to further collaboration with multiple academic and industrial groups on the "hot topics" of Fully Homomorphic Encryption (FHE) and Multi-Party Computation (MPC). This collaboration led Smart to write a series of ground-breaking papers with researchers from IBM Research (T.J. Watson), including the first experimental implementation of FHE technology [**Smart-4**], highlighted as one of the top ten emerging technologies in MIT's Technology Review for 2011, and was featured in a Scientific American article in 2012. In addition, joint work with Univ. Aarhus (Denmark) demonstrates that FHE technology improves the performance of other protocols, such as MPC. It

represents state-of-the-art analysis and possible commercial and governmental applications, via a new spin-out Dyadic Security (with colleagues from Bar-Ilan), are being explored.

Exemplars of Academic Leadership:
The CG provides academic leadership to the worldwide cryptologic community. Smart and Stam are elected directors of the IACR (the international learned society for cryptology), with Smart also on the editorial board of the Society's journal since 2002. The IACR runs the seven annual leading conferences and workshops in the area (*CRYPTO*, *EUROCRYPT*, *ASIACRYPT*, *CHES*, *FSE*, *PKC*, and *TCC*). Of the 42 such meetings between 2008 and 2013, CG members have served on Programme Committees 38 times. Oswald will be Programme Chair of *EUROCRYPT* in 2014 and 2015, and Smart was Programme Chair of *EUROCRYPT* in 2008. The Group also organized *EUROCRYPT* 2012 in Cambridge (UK). At these events, Bristol authors won best paper awards (*ASIACRYPT 2008* [**Smart-3**], *CHES 2012* [**Page-4**], *FSE 2009* [**Stam-3**], *FSE 2010*). (Source: http://www.iacr.org/cryptodb/). Smart held a Visiting Professorship position at ENS Paris (2010-11), and was co-organizer of the six-month Isaac Newton Institute programme that celebrated Alan Turing's centenary in 2012.

The BIG group have engaged in activities which sustain the core discipline of HCI, have developed emerging communities using Group interests, and chair key Program Committees or conferences in the field, including three ACM conferences, *Tangible, Embedded and Embodied Interaction 2009* (Fraser), *MobileHCI 2012* (Subramanian) and *Tabletops and Interactive Surfaces 2008* (Subramanian). Further contributions to Programme Committees include associate chairs at *CHI*, *TEI* and *Mobile HCI* (all Fraser and Subramanian), as well as *CHI Work In Progress* (Coyle), and ICT4Sustainability (Preist). Elected memberships include Marie Curie Fellows Association (Coyle) and the Royal Society of Arts (Fraser). Best paper awards include *CHI 2012* [**Subramanian-4**], *CHI honourable mentions* [**Coyle-3**, **Preist-2**, **Subramanian-1,3**], and *CloudCom* (Preist).

VIL hosted *BMVC 2013* (Mirmehdi, Burghardt and Mayol-Cuevas co-chairs). VIL's editorial duties include various journal editorial boards, including editing special issues; such as a special issue of *IEEE J. Selected Topics in Signal Processing on Emerging Technologies for Video Compression* (Bull) and the *Virtual Reality Journal* (Mayol-Cuevas). In addition, Mirmehdi has been Editor-in-Chief of the *IET Computer Vision Journal* since 2012. The Group has won numerous best paper/poster awards including: BMVC2009 (Mirmehdi**)**, and *BMVC2012* [**Mayol-Cuevas-4**]. Finally, Mirmehdi was elected Fellow of the International Association of Pattern Recognition in 2010 and Bull became a Fellow of the IEEE in 2012.

The ISL hosted *ECML-PKDD 2012* in Bristol, the premier international forum combining the research areas of machine learning and data mining, which attracted 370 participants. Flach, De Bie and Cristianini were the joint Programme and Conference Chairs. Other major international conferences chaired by ISL members include *ACM Conference on Knowledge Discovery and Data Mining – 2009* (Flach), *Integrated Uncertainty Modelling and Applications* (Lawry), *Integrated Uncertainty in Knowledge Modelling and Decision Making* (Lawry), and *IEEE Fuzzy Systems Conference – 2010* (Martin). Editorial roles include Editor-in-Chief of the *Machine Learning Journal* (Flach), editor for the journals *Proteins* and *BioEssays* (Gough), associate editor of the *IEEE Transactions on Evolutionary Computation* (Kovacs, 2004- 2010), and Guest Editor of special issues of *Annals of Operations Research* and *IEEE Transactions of Fuzzy Systems* (Lawry) and *Current Opinion in Structural Biology* (Gough).

The MG provides academic leadership to related communities, including computer architecture, verification, and high performance computing. McIntosh-Smith sits on the Programme Committees of major HPC conferences including *IEEE/ACM SuperComputing*, *International SuperComputing*, the *MULTIPROG HiPEAC* workshop, *AHPCS*, *IWOCL*, and also chaired the *European Manycore and Reconfigurable Supercomputing Conference* from 2010-11. He is a member of the Scientific Committee for the EPSRC-funded *Network on Numerical Algorithms and High Performance Computing*, and a member of the executive board for the EPSRC CCP on *Algorithms and Software for Emerging Architectures (ASEArch)*. He has sat on EPSRC's Research Infrastructure Strategic Advisory Team since 2011. May is a Fellow of the Royal Society and the Royal Academy of Engineering, whilst Pradhan is a Fellow of both the ACM and the IEEE.