Environment template (REF5)

Institution: University of Warwick
Unit of Assessment: UOA 11 – Computer Science and Informatics

a. Overview The Department of Computer Science is one of nine departments in the Faculty of Science. It is housed in a dedicated state-of-the-art 35,500ft^2 building in a recently completed £96.4M quadrangle, where it is flanked by the Mathematics Institute and Department of Statistics, the International Manufacturing Centre and Digital Laboratory, and the International Institute for Product and Service Innovation (which supports technology transfer and interaction with business). This strategic central location highlights: (i) its close affinity with mathematics, statistics and engineering, in particular in the areas of discrete mathematics, data science and image processing; (ii) its underpinning role in interdisciplinary research, highlighted through its strength in computational biology, complexity science and scientific computing; (iii) its role in business, innovation and knowledge transfer, as demonstrated by its numerous start-ups.

The Department has three research divisions, each led by approximately nine academics: **Methodologies and Applications (RD-MA)**; **Systems and Software (RD-SS)** and **Theory and Foundations (RD-TF).** In addition, it plays a leading role in five externally funded inter-/multi-disciplinary research centres: **Centre for Discrete Mathematics and its Applications (RC-DIMAP)**, funded by a £3.8M EPSRC Science and Innovation Award; **Warwick Complexity Complex (RC-CC)**, funded by £11.2M in EPSRC Doctoral Training Centre grants in Complexity Science; **Centre for Molecular Organisation and Assembly in Cells (RC-MOAC)**, funded by a £5.4M Doctoral Training Centre grant; **Centre for Scientific Computing (RC-CSC)**, which coordinates UK short-course training in high-performance computing on behalf of the EPSRC, and which is part-funded by a £3M e-Infrastructure grant; **Warwick Institute for the Science of Cities (RC-WISC)**, which has been awarded a £4M Doctoral Training Centre grant in Urban Science. RC-CSC, RC-DIMAP and RC-WISC are hosted in the Computer Science departmental building.

b. Research strategy The past five years have seen significant growth in the Department's research activities: Research income has increased from a total of £2.04M during the last assessment period to £6.14M in this period; the number of doctoral degrees awarded has increased by 53%. Physical growth has been matched by improved quality: academics in the Department have received 14 personal research fellowships/awards from open competitions. A major change since the last assessment has been the restructuring of research activities into three divisions in order i) to consolidate excellence in the Department's areas of strength and ii) to promote inter-/multi-disciplinary research; eight new professors have been appointed to drive this forward (Cormode, Jarvis, Kral, Li, Lu, Procter, Rolls, Sviridenko). The Department has three strategic objectives, which have undergone planned revision during this assessment period:

SO1: To engage in inter-/multi-disciplinary research to improve quality of life, health, national security, education and social cohesion. Examples during this assessment period have included: (i) pioneering research on automating the cycle of scientific experimentation from hypothesis generation, experiment design and implementation to knowledge discovery – identified as one of the top 10 scientific discoveries of 2009 by *TIME* magazine [ML1, *Science*]; (ii) the first computational model to link oxytocin ("trust" hormone) release, single neuronal activity and network activity, reported worldwide (including BBC News, *Washington Post*, *Scientific American*, Reuters) and offering further proof that breastfeeding promotes the maternal bond through a biochemical process [JF2, *PLoS Comput. Biol.*]; (iii) the application of innovative computational methods to the analysis of social media data from the 2012 London riots, which was featured by *The Guardian*, *The Independent*, the BBC and others, was presented to the Shadow and Home Secretaries, and won the 2012 Award for Data Journalism [RP2, *Int. J. Soc. Res. Meth.*]; (iv) the complete solution to the long-standing overhang problem [MP2, MP3, *Amer. Math. Monthly*], which won the triennial Mathematical Association of America 2011 David Robbins Prize and received worldwide publicity.

SO2: To develop new computing science techniques and seek methods of application and commercialisation. Examples have included: (i) the first comparative analysis of local, self-symmetric, non-stationary image representation [GM3, *IEEE Trans. Image Process.*], which has been patented and commercialised in competitive fingerprint products, is licensed to suppliers in the Netherlands, France, the US, China and India, and is used in over 50,000 access controls per day to UK construction sites; (ii) the first effective method for enhancing sensor pattern noise in digital images [CTL1, *IEEE Trans. Inf. Forensics Security*], which is being used commercially for intellectual property protection, and for criminal, terrorist and child pornography investigations (including the analysis of millions of images by INTERPOL).

SO3: To provide leading advice and knowledge transfer to government and industry, and promote jobs and growth through technical innovation. Examples have included: (i) the first head-to-head comparison of scalability, power and performance of GPU, CPU and PowerPC technology, which featured in *HPCWire*, *Scientific Computing*, *India Times*, *Global Times* and others, and has subsequently informed high-performance-computing procurement at the UK MoD and Rolls-Royce [SJ3, *Comput. J.*]; (ii) pioneering research in computational neuroscience [JF4, *Nature Molecular Psychiatry*], which provides a better understanding of how mental disorders such as depression alter the brain's functional connections, featured in over 1,000 reports worldwide (e.g. CNN, *The Times*, *Scientific American*), promoting early diagnosis and therapy; (iii) leading research commissioned by the NHS on the impact of IT on patient care [RP1, *PLOS Med.*], which has contributed to healthcare policy in the UK, Australia, Belgium, UAE and Saudi Arabia.

Evidence of achievement during the assessment period, contribution to strategic objectives and future strategic plans

Division: Methodologies and Applications (RD-MA) Profs Feng (JF), Li (CTL), Lu (WL), Rolls (ER), Drs Liakata (ML), Rajpoot (NR), Sanchez (VSa), Timofeeva (YT)

I. Examples of research achievements during the assessment period:

   Computational Neuroscience: Feng's EU- (FP7-ICT 213219, £275,240) and EPSRC- (EP/E002331/1, £101,268) funded research, with the Babraham Institute Cambridge, the Oxford Centre for Computational Neuroscience and others, presents a novel approach to understanding oscillatory activity in regulating biological processes, the algorithms of which now feature in the Matlab and R-package [JF1, *PLoS Comput. Biol.*]. [JF2, *PLoS Comput. Biol.*] presents the first computational model linking oxytocin release, single neuronal activity and network activity, see SO1, above. [JF4, *Nature Molecular Psychiatry*] reports pioneering research that provides a better understanding of how mental disorders alter the brain's functional connections, see SO3, above. [ER1, *Behav. Brain Res.*] presents a new theory of hippocampal computation, which has impacted on work by distinguished researchers on aging (Gilbert, Eichenbaum), neurogenesis (Wilson) and hippocampal structure and function (Lomo, Kesner). Timofeeva's BBSRC-funded work (BBSRC BB/H011900/1, £257,223) with UCL and Bonn University makes a major contribution through the novel combination of electrophysiological, optical, pharmacological and modelling approaches [YT4, *Nat. Neurosci.*]. Other notable research [ER4, *Nat. Rev. Neurosci.*] charts the application of computational neuroscience approaches to the understanding of schizophrenia.

   Bioimage Analysis: The division has a proven track record in biomedical image analysis, with particular applications in digital pathology and cancer bioimaging. Rajpoot, supported by the Qatar Foundation (NPRP5-1345-1-228, £118,165) and with Georgia Tech, has developed new solutions to the alignment of multi-tag bioimages [NR1, *PLoS ONE*]. New methods of multilateral filtering have been developed and applied to the reduction of speckle in ultrasound imaging [NR3, *Pattern Recognition*] and intracellular diffusion [NR4, *J. Comput. Neurosci.*], resulting in two patents (GB2012/050517, GB1212090.3) and funding from the BBSRC (BB/K018868/1, £244,176) and GE Healthcare. Sanchez, supported by an NSERC Canada Fellowship and with the University of British Columbia, has developed new methods for exploiting the inherent symmetrical properties of medical imaging data [VSa1, *IEEE Trans. Med. Imag.*] and a novel 3-D scalable compression method for images with optimised volume of interest coding [VSa2, *IEEE Trans. Med. Imag.*].

   Machine Learning and Biomedical Text Mining: Lu, with Fudan and Shanghai Universities, has created a new mathematical framework for the multi-stability of almost-periodic solutions of recurrently connected neural networks with delays [WL3, *IEEE Trans. Neural Netw.*]. Liakata's pioneering work automating the cycle of scientific experimentation is reported above, see SO1. With EMBL-EBI in Cambridge and the Royal Society of Chemistry, and funded by a Leverhulme Trust Early Career Fellowship, Liakata has also analysed the benefits of different automatic scientific discourse annotations in cancer risk assessment [ML3, *BMC Bioinformatics*].

   Digital Forensics: Li, supported by funding from the EU (Marie Curie IAPP, £1,075,226), industry (Forensic Pathways Ltd, £93,117) and the TSB (Milamber Digital, £132,689), has developed the first effective method of enhancing sensor pattern noise in digital images [CTL1, *IEEE Trans. Inf. Forensics Security*], resulting in several patents (GB2467767, GB2010/050247, EU10711923.2). The applications of this research are documented in SO2, above. Li has also developed the first approach to attenuating de-mosaicking distortion on sensor pattern noise through colour decoupling [CTL2, *IEEE Trans. Circuits Syst. Video Technol.*] and new approaches to content-based image retrieval [CTL4, *Pattern Recogn*].

II. Research vision, including strategic plans:
The division's acknowledged expertise in modelling, imaging and forensics has enabled it to contribute to all three of the Department's strategic objectives during the assessment period. Amongst the division's strategic plans are: (i) pursuing its research in inter-/multi-disciplinary healthcare (SO1), including new compiling techniques in synthetic biology, histopathology image analysis and cancer bioimaging; (ii) commercialising new techniques in multimodal biometrics, forensic image analysis and pattern recognition (SO2) and (iii) providing health policy advice (SO3) on the diagnosis of mental disorders, based on computational modelling and the analysis of large clinical datasets (ADNI, Alzheimer's Disease Neuroimaging Initiative and IMAGEN, the EU-funded behavioural neuroscience study of mental health in teenagers).

Division: Systems and Software (RD-SS) Profs Cormode (GC), Jarvis (SJ), Procter (RP), Drs Ciucu (FC), He (LH), Joy (MJ), Leeke (MLe), Martin (GM)
I. Examples of research achievements during the assessment period:
This division plays a leading role in Warwick's interdisciplinary Centre for Scientific Computing.

Parallel and Distributed Computing: Jarvis's Royal Society- (IF090020 £125,000) and MoD-funded (CDK0660/0724 £414,496, KTP006740 £204,002) research, in collaboration with the University of Oxford, LLNL, Rolls-Royce and AWE, resulted in an internationally reported analysis of emerging HPC architectures [SJ3, *Comput. J.*], see SO3. Subsequent collaboration with Sandia National Laboratories and Intel [SJ4, *J. Parallel Distr. Com.*] led to an R&D Top 100 Award in 2013. This research has resulted in new HPC codes, e.g. DL-POLY4 (EPSRC EP/F010834/1), and a new ALE code for laser fusion energy (EPSRC EP/I029117/1). Dr He, in a project with Hunan University, funded by the Leverhulme Trust (RPG-101, £62,390) and NSF China, has developed a new fast Remote Procedure Call mechanism for virtual machines, which is an order of magnitude faster than industry solutions [LH1, *IEEE Trans Parallel Distrib. Syst.*]. With INRIA, Jarvis has developed new coverage optimisation algorithms for mobile sensor networks [SJ1, *IEEE Trans. Mobile Comput.*] and in EPSRC-funded research (EP/F000936/1, £73,951) with VU Amsterdam and CSIRO Australia, he has produced new systematic solutions for service differentiation in P2P streaming services [SJ2, *IEEE Trans Parallel Distrib. Syst.*].

Communication Networks and Data Science: Ciucu, with the University of Toronto, TU Berlin and Deutsche Telekom, has significantly advanced the understanding of end-to-end delays (i) in networks with fractal traffic and finite regimes [FC2, *IEEE Trans. Inf. Theory*], and (ii) in the scaling of packet networks, overturning a 1960s' dogma [FC3, *IEEE/ACM Trans. Netw.*]. Ciucu's discipline-hopping research on power grids was the first to identify an isomorphism between network buffers and batteries, with the potential to significantly reduce carbon footprints by better matching supply and demand [FC1, *IEEE J. Sel. Area Comm.*]. With Rutgers, HKUST and Aarhus Universities, and funded by the NSF (No.1144502, $698,995), Cormode has developed a formal model and analytic bounds for monitoring complex functions of continually varying values over multiple observers [GC1, *J. ACM*], and new algorithms for the anonymisation of social network (labelled graph) data [GC3, *VLDB J.*]. With Google Inc., he has developed a new concept of streaming interactive proofs for outsourced computations [GC4, *ACM Trans. Algorithms*]. Cormode has received 14 patents.

Software and Tools: Joy, with EU funding (MALog, €111,311), has developed new tools to investigate similarities between source code [MJ1, *IEEE Trans. Comput.*], which have subsequently been adopted by InfoSys (India) and others. Procter's JISC Research Tools-funded (£115,000) work on methods and tools for social media analysis was applied to data from the 2012 London riots [RP2, *Int. J. Soc. Res. Meth.*], winning the 2012 Award for Data Journalism, see SO1. NHS-commissioned research on the impact of IT on patient care, with Imperial, Edinburgh and Manchester, has contributed to healthcare policy in several countries [RP1, *PLOS Med.*], see SO3.
II. Research vision, including strategic plans:
The division's recognised expertise in high-performance computing, and its recent contributions to the field of data science, have enabled it to contribute to all three of the Department's strategic objectives during the assessment period. Its strategic plans include: (i) developing technologies for urban science, e.g. energy harvesting sensors for mass urban deployment (SO1); (ii) improving power efficiency, scalability and performance of HPC codes on emerging computing architectures, together with on- and off-line data analytics for the exploration of high-frequency data streams (SO2); (iii) the use of "big data" to support decision-making (e.g. policing) and the use of social media as a "living laboratory" for the study of innovation processes (SO3).

Division: Theory and Foundations (RD-TF) Profs Czumaj (AC), Kral (DK), Paterson (MP), Sviridenko (MS), Drs Ene (AE), Englert (ME), Jurdzinski (MJu), Lazic (RL), Murawski (AM), Tiskin (AT)

I. Examples of research achievements during the assessment period:

This division plays a leading role in the Centre for Discrete Mathematics and its Applications.

Automata Theory, Model Checking, Verification, and Controller Synthesis: Murawski, with Oxford, has developed (i) the first automata-theoretic characterisation of higher-order recursive schemes, solving a long-standing problem from the 1970s [AM1, LICS'08]; (ii) a new compositional verification tool for probabilistic programs that outperforms existing solutions [AM2, *Form. Methods Syst. Des.*] (EP/G069158/1, £290,346); (iii) the solution to a major shortcoming (the bad-variable problem) in modelling references using game semantics [AM3, LICS '11], underpinning research on verifying Java programs (EP/J019577/1, £209,084). Kral, with Charles University and Georgia Tech, has developed a linear time algorithm for first-order model checking [DK1, *J. ACM*], described as "one of the most general meta-algorithmic results in parameterised complexity". With CNRS (France) and Torino University, and funded by the EPSRC (EP/E022030/1 £118,458), Jurdzinski has introduced novel "countdown games", which have become a standard complexity tool for timed automata [MJu2, *LMCS*]. Lazic has developed new algorithmic properties of logics and automata for structures with unbounded data [RL1, *ACM T Comput Log.*].

Sublinear Algorithms and Combinatorics: Czumaj, with Sohler (Dortmund), has developed the first (1+epsilon)-approximation sublinear-time algorithm for estimating the cost of a minimum spanning tree in metric graphs [AC1, *SIAM J. Comput.*], cited as highly significant by Princeton, MIT and IBM (EP/G064679/1, £296,846). Kral, in EU-funded research (ERC Starting Grant, €849,000), has used linear programming methods to solve the 1970s' conjecture of Lovasz and Plummer on the existence of exponentially many perfect matchings in cubic bridgeless graphs, and was awarded the 2011 European Prize in Combinatorics [DK2, *Adv. Math.*]. With AT&T Labs, Dartmouth College, Tel Aviv University and MSR, Paterson has developed the complete solution to the long-standing overhang problem [MP2, MP3, *Amer. Math. Monthly*], see SO1.

Approximation, Online Algorithms and Constrained Optimisation: Under an EPSRC Postdoctoral Fellowship (EP/F043333/1, £204,382) and with Bonn University, Englert has developed an algorithm which provides best quality guarantees for packet forwarding in network switches, and outperforms all other methods [ME1, *SIAM J. Comput.*]. Czumaj and Englert have developed best-known algorithms for two fundamental online problems: buffer management [AC4, *STOC'11*] and weighted caching [ME3, *SODA'12*]. Sviridenko, with IBM Research and Bologna University, has developed the best-known approximation algorithms for multidimensional packing problems [MS1, *SIAM J. Comput.*]. With Princeton, he has exponentially improved approximation algorithms for broadcast scheduling [MS2, *SIAM J. Comput.*] and produced a new harmonic algorithm for a 3-D strip-packing problem, which has found application in cloud computing, steel manufacturing and data centre management [MS4, *SIAM J. Comput.*] (EP/J021814/1, £360,972). Tiskin, supported by a Royal Society Leverhulme Trust Senior Research Fellowship (LT2009/AT), has developed a new approach to approximate string comparison based on matrix distance algebra [AT1, *Algorithmica*].

II. Research vision, including strategic plans:

Through RC-DIMAP, this division leads an internationally competitive programme of research in discrete modelling, algorithmic analysis and combinatorial (discrete) optimisation. This will continue to support the Department's strategic objectives, in particular in areas of inter-/multi-disciplinary research (SO1). The division will also be key to delivering the Department's second strategic objective (SO2). Plans include: addressing open problems in areas including algorithmic game theory (EP/G069034/1, £351,899) (complexity of parity and mean-payoff games, and approximation of Nash equilibria); the verification of infinite-state systems (complexity/decidability of reachability in Petri nets); new algorithms for fundamental combinatorial problems; randomised rounding algorithms for energy-efficient scheduling and supply chain analytics.

c. People: How staffing strategy relates to the unit's research strategy and physical infrastructure The Department's staffing strategy has been (i) growth and (ii) strengthening the three newly created research divisions. This has been achieved by a mix of promotions and new appointments, at both senior and junior levels. Thanks to the University's strategic research collaboration within Birmingham Science City, the Department has benefitted from the £9.6M **HEFCE Strategic Development Fund,** which has funded 22 Research Alliance Fellows at Birmingham and Warwick, including in HPC. **The Department's aim is to grow by a further 40%**

over the next ten years, with 15 additional academic staff. As part of the University's vision to strengthen its mathematical sciences research, in 2015 it is proposing to build a **£20M, 40,000ft^2 Department extension, promoting interdisciplinary collaboration between Computer Science, Mathematics and Statistics.** Appointments during the assessment period were as follows: **RD-MA** Prof Rolls (Oxford), Dr Liakata (EMBI, Cambridge), Dr Sanchez-Silva (Berkeley); **RD-SS** Profs Cormode (AT&T Labs) and Procter (Manchester), Drs Leeke (Warwick) and Ciucu (TU Berlin); **RD-TF** Profs Kral (Charles University) and Sviridenko (IBM Watson), Drs Coja-Oghlan (Edinburgh), Ene (Urbana-Champaign), Englert (RWTH Aachen), Murawski (Leicester) and Zivny (Oxford). In addition, one third of existing staff were promoted: to Professor (Coja-Oghlan, Jarvis, Li); to Reader (Cristea, Joy); to Associate Professor (He, Jhumka, Jurdzinski, Timofeeva).

Supporting the career development of researchers The University signed the UK Concordat to Support the Career Development of Researchers in 2008 and has recently been awarded the **HR Excellence in Research Award**. Since 2008, both the University and the Department have put in place several mechanisms for implementing the Concordat. The University supports ECRs through the new **Learning and Development Centre (LDC),** which delivers a programme of support and training leading to an accredited **Postgraduate Award in Transferable Skills**. Established academic staff benefit from a new recruitment and retention policy designed to search for, appoint, nurture and reward the most able academic, research and support staff. Other University-wide initiatives include: the creation of an **Institute of Advanced Study (IAS)**, which provides a range of early career activities; **Wolfson Research Exchange,** a forum for interdisciplinary collaboration, and **Research Support Services (RSS)**, for maximising research impact and knowledge transfer.

In addition, Computer Science supports the development of ECRs and established academic staff through: a new promotions advisory committee; start-up funds for new academics; reduced teaching load for ECRs; a new process of internal review (and feedback) on all research applications by senior staff; mentors for new staff; annual reviews; research sabbaticals (taken by 11 staff during the assessment period). In 2011 the Department created the **John Buxton Lectureship** for a promising early-career, post-doctoral academic, now held by Leeke.

Personal research fellowships/awards from open competitions held during REF period
14 awards: Coja-Oghlan: ERC Starting Grant (2011-16), *Phase Transitions and Computational Complexity,* now at Goethe University; **Englert**: EPSRC Postdoctoral Research Fellowship (2008-2011), *Randomisation in Online Algorithms*; **Feng**: Royal Society Wolfson Research Merit Award (2011-2016), *Bridging the gap between fMRI and genome-wide data*; **Hu**: EU Marie Curie Research Fellowship (2011-2013), *Digital Image and Video Forensics*; **Jarvis**: Royal Society Industry Fellowship (2009-2013), *HPC application performance modelling*; **Kral**: ERC Starting Grant (2010-2015) *Classes of Combinatorial Objects*; **Liakata**: Leverhulme Trust Early Career Fellowship (2010-2013), *Reasoning with Scientific Papers*; **Liakata**: IBM Faculty Award; **Lu**: EU Marie Curie Research Fellowship (2012-2014), *Nonlinear Dynamical Systems in Computational Neuroscience*; **Sach**: EPSRC Postdoctoral Research Fellowship (2011-2014), *Pattern Matching Algorithms*, now at Bristol; **Savani**: EPSRC Postdoctoral Research Fellow (2006-2009), *Computing Equilibria in Games*, now at Liverpool; **Sviridenko**: Royal Society Wolfson Merit Award (2012-2017), *Randomised Rounding Algorithms*; **Tiskin**: Royal Society Leverhulme Trust Senior Research Fellowship (2009-10), *Efficient Parallel String Comparison*; **Zivny**: Royal Society University Research Fellowship (2013-2018), *Optimisation of Separable Functions*, now at Oxford.

International staff appointments, recruitment and visiting scholars Approximately half of new academic appointments have been international recruits: Cormode (AT&T Labs, New Jersey), Ciucu (TU Berlin), Ene (Urbana-Champaign), Englert (RWTH Aachen), Kral (Charles University, Prague), Räcke (TTI Chicago), Sanchez-Silva (Berkeley), Sviridenko (IBM Watson). Three academic staff have left to take up international professorships: Peled (Bar Ilan University, Israel), Räcke (TU München, Germany), Coja-Oghlan (Goethe University, Germany).

The Department has a thriving visiting scholar programme. During the assessment period visitors have included – **RD-MA:** Dr Chen (Fudan), Prof Deco (UPF Barcelona), Prof Dongyun (Hunan), Prof Khan (Lawrence Berkeley National Laboratory), Prof Leary (Forensic Pathways), Prof Meunier (Paris Descartes), Prof Nattkemper (Bielefeld), Prof Olivo-Marin (Institut Pasteur), Prof Osipov (Nizhny Novgorod), Prof Peng (Hunan), Prof Shah (University of Central Florida), Prof Shiau (Houston), Prof Sorell (Adelaide), Dr Wu (Babraham Institute). **RD-SS:** Dr Chen (Hunan), Prof Cowlishaw (IBM), Gaudin, Herman, Vadgama (AWE), Dr Harfield (Tesella), Dr Papanikolaou (HP Research), Dr Ralston (Red Oak Consulting), Dr Sun (Hunan), Dr Tan (INRIA, Chinese

Academy of Science). **RD-TF:** Prof Cole (NYU), Prof Feige (Weizmann), Prof Flajolet (INRIA), Prof Gupta (CMU), Prof Indyk (MIT), Prof Iwama (Kyoto), Prof Knuth (Stanford), Prof Sudakov (UCLA), Prof Upfal (Brown), Prof Valiant (Harvard), Prof Wattenhofer (ETH), Prof Zwick (Tel Aviv).

Evidence of how the submitting unit supports equalities and diversity The University has a **Single Equality Scheme** and associated Equality Objectives, linked to the *Concordat*, and covering full-time, part-time and fixed-term research staff and students. The University's **Commitment to Equality and Diversity** is monitored through the annual Pulse Staff Survey and staff annual reports; the Department's Equality and Diversity Officer reports directly to the University's Equality and Diversity Committee. In 2013, the University achieved an institutional **Athena Swan Charter for Women in Science Silver Award,** recognising commitment to advancing women's careers in STEMM subjects in higher education.

PGR recruitment The Department has 50 to 60 PhD students: two thirds supervised by the Department; the remainder by research DTCs. It attracts high-quality PGR students, most with a first class degree, or Merit/Distinction at Masters level. Applicants with work experience are encouraged. Funding sources include research grants, CASE awards & international scholarships.

PGR supervision, progress monitoring and resourcing PGRs are assigned a supervisor, possibly a co-supervisor from another department, and an advisor. Weekly meeting record forms are completed by students and supervisors. Students have dedicated office space in close proximity to their supervisors, and all students are provided with a new high-specification desktop computer and a travel budget. The Postgraduate Monitoring Committee reviews each student's progress annually, based on the student's annual report and presentation at the Department's Postgraduate Colloquium (mini-conference), held every summer.

PGR training and support mechanisms include: the **Postgraduate Hub**, a dedicated study facility offering workspace and training programmes (on e.g. dissertation writing, literature searching, referencing and practical paraphrasing); and **Wolfson Research Exchange**, which operates the PhD Network, an interdisciplinary community offering events and online networking on topics including work-life balance and stress management. The Department pays for all PGRs to be registered for the **Postgraduate Certificate in Transferable Skills**. Supported by their supervisors/advisors, students complete 6 training courses on e.g. literature reviews, planning research, verbal communication, intellectual property. All PGRs develop a **Warwick Portfolio**, an online space in which they log personal and professional development.

d. Income, infrastructure and facilities

Provision and operation of specialist infrastructure and facilities All Department researchers have access to the following specialist infrastructure and facilities, operated by 8 dedicated technical staff: a camera array (48 Sony firewire cameras backed by 48 PCs/storage, custom synchronisation/networking); a 4m x 2m 3-D back-projected 2100 x 1050 display operated by two 4000-lumen projectors; a graphics rendering cluster; 18 IBM Z-Pro graphics workstations with 3-D facilities, and high-performance-computing facilities including (i) a 6,000-core compute cluster with multi-terabyte GPFS, (ii) a 1,000-core COW for task farming, (iii) multi-tiered data storage, (iv) multiple 1 Gb VLANs to all desktops and unrestricted 10Gb connections to research servers (high-volume data transfers over JANET to facilitate national and international interaction), (v) dynamically provisioned data-centre facilities. The Department has an Access Grid node for multi-way videoconferencing and access to 6 Cisco Telepresence suites.

Investment (both current and planned) in infrastructure and facilities Upgrades to computing facilities have included: £600k of investment in general computing infrastructure across 3,700ft^2 of research laboratory space; the refurbishment of a 1,500ft^2 electronics laboratory; a new 1,000ft^2 server room for PhD students; the 2012 £3M e-Infrastructure upgrade of high-performance-computing and storage facilities operated by the Centre for Scientific Computing. In 2015, the University is proposing to build a **£20M, 40,000ft^2 Department extension**, see Section c.

The Department has also benefitted from the following major investments: (i) the £50M multidisciplinary **International Digital Laboratory** (opened 2009) combining expertise in manufacturing, computer science, psychology, medicine and mathematics and housing the world's first four-panel High Dynamic Range display, an e-security lab (including a Faraday cage) and a lab car (supplied by Jaguar Land Rover) for research into on-board sensors, smart dashboards, etc; (ii) the £12M **International Institute for Product and Service Innovation**, which supports collaboration with local SMEs; (iii) the £45M **Birmingham Science City Research Alliance**, which has brought a new semiconductor cleanroom and a gait lab for motion analysis to Warwick.

Information on the research funding portfolio, including future plans Year-on-year research income has increased in all areas over the assessment period (see Table 1), driven by the Department's Research Committee, whose priorities for this period have been to (i) diversify funding sources and (ii) increase industry and EU funding, by (iii) introducing a mentoring scheme for grant writing, and (iv) establishing a research funding incentive scheme.

Table 1: Year-on-year research income, rounded to the nearest £k, for period 8/2007-8/2013.

	07-08	08-09	09-10	10-11	11-12	12-13	Increase since 07-08
Research Councils	£504k	£578k	£744k	£720k	£770k	£916k	82%
UK industry/ charities/gov	£44k	£132k	£146k	£171k	£293k	£384k	773%
EU / other	£37k	£117k	£165k	£232k	£348k	£428k	1,057%
Total	£585k	£827	£1,055k	£1,124k	£1,410k	£1,728k	195%

The Department has seen a rise in **research income per FTE from £20,950 in 2007-2008 to £70,822 in 2012-13**. Total research income has increased from £2.04M in the previous assessment period to £6.14M in this assessment period, an increase of 201%, see Table 2.

Table 2: Total research income in previous assessment period and this assessment period.

	Previous period	This period	Increase
Research Councils	£1,485k	£3,728k	151%
UK ind / char / gov	£160k	£1,126k	604%
EU / other	£395k	£1,290k	227%
Total	£2,040k	£6,144k	201%

REF4c logs compute time on the UK National Supercomputing Service; it does not take into account other in-kind contributions, including GE pathology workstations, equipment and data from AT&T/IBM, EMBL-EBI software, test vehicles from JLR, access to supercomputers at LLNL etc.

Future plans: *International*: Recently established international research partnerships will have a major impact on the funding portfolio, reflecting the Department's leading role in three major University initiatives: the New York-based Center for Urban Science and Progress (CUSP); the joint Centre for Computational Systems Biology, based at Fudan University; the partnership (including staff exchange) with the Department of Computer Science and Engineering at Qatar University. ***National*:** Funding will be attracted through recently established strategic partnerships with (i) universities (in priority areas: discrete mathematics with Queen Mary, London; urban science with Kings College London; HPC with Birmingham and Nottingham); (ii) local government (e.g. the City of Birmingham in data and urban science) and (iii) industry (e.g. Bull Info. Systems).

Information on consultancies or professional services: *Department Spin-outs/Directorships*: Warwick Warp; Allinea Software; Concurrent Thinking; Pattern Analytics. *Consultancy*: Airparks; AT&T Labs-Research; AWE; Bull Information Systems; Deutsche Bank; Forensic Pathways; GCHQ; HE Academy; NatCen; National Police Improvement Agency; IBM Research; Red Oak Consulting; Rolls-Royce; Sandtable; Scottish Justice Affairs Service; *The Guardian*, Yahoo!.

e. Contribution to the discipline/research base through national/international collaboration: Support for and examplars of research collaborations

Academic: The Department leads the multidisciplinary *Centre for Discrete Mathematics and its Applications*, funded by a £3.8M EPSRC Science and Innovation Award. The centre exerts international influence on the field through its recognised programme of research in discrete modelling, algorithmic analysis and combinatorial (discrete) optimisation, and has engendered national/international collaborations with world-class researchers, including Berkeley (Sinclair), Cambridge (Kelly, Thomason), CMU (Gupta), Harvard (Valiant), Max-Planck (Mehlhorn), MIT (Indyk, Levi), Oxford (Goldberg, Ouaknine), Stanford (Knuth), Tel Aviv (Alon, Zwick), Tokyo (Kawarabayashi), Weizmann Institute (Feige), and an alliance with industrial research partners including AT&T (Johnson, Thorup), Google (Mirrokni), IBM (Onak), Microsoft (Talwar). Resulting contributions to the research base include Paterson's solution to the long-standing overhang problem (triennial Mathematical Association of America 2011 David Robbins Prize) and Kral's solution to perfect matchings in cubic bridgeless graphs (2011 European Prize in Combinatorics).

Industry: The Department's influential image-processing research has raised the profile of digital forensics, both as an academic discipline (launch of an international journal in digital crime and forensics) and as a driver for regional growth (creation of Warwick Warp Ltd; leading role in

Forensic Pathways Ltd and Pattern Analytics Ltd). World-leading products have resulted from this collaboration, used by INTERPOL for source camera identification of paedophile images and by police forces in Europe, Japan and Australia in criminal cases.

Government: The Department is leading HPC research on national nuclear security, collaborating with UK AWE, and the US national laboratories (LANL, LLNL and SNL). This research has had a significant impact on the procurement of HPC systems at AWE and LANL and the design of HPC architectures, has influenced the design of production codes, and has generated tools and techniques to support scientific delivery at those laboratories. In addition, it has led to the creation of two internationally leading companies, Streamline Computing Ltd and Allinea Software Ltd.

Support for and examplars of interdisciplinary research

1) The Department hosts the *Centre for Scientific Computing (RC-CSC)*, an interdisciplinary research environment which develops and shares computational expertise for the resolution of significant research goals. It coordinates UK short-course training in HPC on behalf of the EPSRC, and offers HPC services and training to industry (e.g. the MoD, Rolls-Royce, Intel and Bull).

2) The Department is a key partner in the interdisciplinary *Warwick Complexity Complex*, funded by £11.2M in EPSRC DTC grants. The aim of the centre is better to understand, adapt, design and control complex systems, through collaborations with e.g. HP, the Dept of Health, UK Met Office, BT, National Grid, GlaxoSmithKline. Notable contributions to the research base are in computational neuroscience (e.g. aging and neurogenesis) and epidemiology.

How research collaborations have informed research activities and strategy

The University was the only European partner in the creation of the new interdisciplinary *Center for Urban Science and Progress* (CUSP; cusp.nyu.edu) in New York, formed by a consortium of world-class institutions, led by NYU and NYU-Poly and including Carnegie Mellon University, the City University of New York, IIT Bombay and University of Toronto. Industry partners include IBM, Cisco, Siemens, National Grid, Xerox, Arup and AECOM. Warwick's contribution to this initiative is led by Jarvis, who will also be heading the new EPSRC Centre for Doctoral Training in Urban Science (EP/L016400/1, £4M) from April 2014. To support these initiatives, the Department has made a strategic decision to build its expertise in Data Science, hiring three new staff (inc. two professors), and making provision for a major new extension. This has steered research activities in new directions, including social media, wireless sensor networks and streaming algorithms, and has led to new strategic partnerships with Birmingham City Council, IBM and KCL.

Exemplars of leadership in the academic community: RD-MA: *Feng*: Chair, Int. Conf. Systems Biology; Fellow, Society of Biology; Royal Society Wolfson Research Merit Award; Editorial Board *Cognitive Neurodynamics*. *Li*: Editor-in-Chief *Int. J. Digital Crime and Forensics*; Chair, EU COST Action IC1106: Integrating Biometrics and Forensics for the Digital Age; Chair, Int. Conf. Forensic Applications and Techniques, 2008, 2009. *Liakata*: Leverhulme Trust Early Career Fellowship; IBM Faculty Award; Workshop Chair, Int. Conf. Computational Linguistics 2013. *Rajpoot*: Associate Editor *IEEE Trans. Biomedical Engineering*; Associate Editor *Machine Vision and Applications*; Chair, Medical Image Understanding and Analysis 2010; *Timofeeva*: Chair, Int. Mathematical Neuroscience Conference (2008-2012). **RD-SS: *Cormode***: ACM Distinguished Scientist; Associate Editor *ACM Trans. Database Systems*; AT&T Advisory Board member; Co-Chair ACM SIGMOD 2013. *Jarvis*: Royal Society Industry Fellowship; Chair, 12th IEEE Int. Conf. Scalable Computing and Communications 2012; Committee Member, Council of Professors and Heads of Computing. *Procter*: Programme Chair: Int. Conf. e-Social Science, 2005-2009; Editor *Health Informatics Journal*. *He*: Editorial Board *J. Parallel and Distributed Computing and Networks*; Workshop Chair, 13th IEEE Int. Conf. Computational Science and Engineering 2010. *Joy*: Programme Chair, 2nd Int. Conf. Education and e-Learning 2012; Member, BCS Academic Accreditation Committee. *Leeke*: AQA Computer Science and ICT Expert Panel. *Martin*: Member, British Standards Technical Committee, IST/37. **RD-TF: *Czumaj***: Chair, 39th ICALP 2012; Chair, LMS Computer Science Committee. *Kral*: Associate Editor *SIAM Journal Discrete Mathematics*; Editorial Board *European Journal of Combinatorics*; ERC Starting Grant. *Paterson*: Scientific Advisory Board, Institute for the Theory of Computing, Berkeley; Goedel Prize Committee (2009-2011); *Sviridenko*: Royal Society Wolfson Research Merit Award; Associate Editor *Operations Research*; Associate Editor *Discrete Optimization*. *Jurdzinski*: PC Co-Chair, FORMATS 2012; Keynote, 35th Int. Conf. on Current Trends in Theory and Practice of CS 2009; *Murawski*: EPSRC Advanced Research Fellowship. *Tiskin*: Royal Society Leverhulme Trust Senior Research Fellowship; Steering Committee, Int. Symp. on High-level Parallel Programming and Applications.