

Institution: University College London (UCL)
Unit of Assessment: 10 Mathematical Sciences

1. Unit context and structure, research and impact strategy

The mathematical sciences at UCL are predominantly represented by the Departments of Mathematics and Statistical Science (“Statistics” below). These are currently housed in separate buildings but work together on teaching, research and impact. Of the 94.15 FTE submitted, 65.6 are in Mathematics, 26.55 are in Statistics and 2 are from the Gatsby Computational Neuroscience Unit. The departments have also submitted 2.1 FTE to other Units of Assessment. Mathematics and Statistics are administratively distinct departments within the Faculty of Mathematical and Physical Sciences (MAPS), whereas the Gatsby Unit is part of the Faculty of Life Sciences. Staff submitted are named in **bold** and those who left before the census date in *italic*.

UCL is currently investing significantly in the mathematical sciences, working towards the establishment of an **Institute for Mathematical and Statistical Sciences (IMSS)** that will see the departments co-located in a refurbished building and an increase in academic staff numbers to approximately 130 FTE over the next 7 years: this target represents a doubling in size compared with 2014, and will significantly enhance UCL’s profile as a major centre for the discipline. IMSS is currently the top strategic priority of the MAPS Faculty. Since REF2014 we have progressed just over half-way to the 130 FTE target: the unit headcount has grown by 50% from 62.95 FTE with four new permanent appointments in each of 2016 and 2017, 11 in 2019 and three in 2020, plus three institutionally funded postdoctoral fellowships – IMSS fellows and a Clifford fellow in 2020. This investment, and the associated increase in activity, has been recognised internationally: in the 2020 QS World Rankings for example, UCL appeared in the top 50 universities worldwide for Mathematics, and was ranked 23 for Statistics and Operational Research (from 47 in 2014).

Research topics covered in our unit include: algebraic geometry; analysis (particularly of PDEs, from both pure and applied perspectives); combinatorics, number theory; numerical methods and scientific computing; differential geometry and geometric analysis; geometric group theory; financial mathematics; fluid dynamics and continuum mechanics; mathematical modelling (including mathematical biology); probability; mathematical statistics; computational statistics; applied statistics and biostatistics. The Clinical Operational Research Unit (CORU) is a sub-unit of Mathematics comprising 4.5 FTE and dedicated to applying tools from operational research, data analysis and mathematical modelling to health care.

We collaborate with a wide range of centres and have partnerships both within and beyond UCL. These include the Centre for Computational Statistics and Machine Learning (CSML) which links Statistics, Gatsby and the Department of Computer Science; the EPSRC/UKRI Centre for Doctoral Training in Geometry and Number Theory (LSGNT) involving UCL Mathematics, King’s College London and Imperial College and coordinated by PI **Singer**; the EPSRC Programme Grant EP/S026347/1 (**Ni** as Co-I) linking UCL with Oxford, the Alan Turing Institute and other partners in rough paths and data science; and UCL’s Met Office Academic Partnership (MOAP) co-led by **Guillas** as Met Office Joint Chair (unique among the six UK MOAPs, in being chaired from a mathematical sciences department).

The unit’s average annual research spend is £4M. The total number of research awards over the period was 201, for a total of £30M. This excludes the LSGNT CDT (see above), starting in 2014 (£4.7M) and renewed in 2019 (£6M): Section 2.3 gives more details.

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The unit produced 1407 research articles (journal articles, reviews, and conference proceedings) during this REF period. We consistently publish two articles per person per year, with just over half resulting from international collaborations.

On 31st July 2020, there were also 25 postdoctoral research associates in the unit that did not meet the REF eligibility criteria but make a valued contribution to our research. In January 2020 there were 85 PhD students in Mathematics and 47 in Statistics, increases from 45 and 31 respectively in 2013.

1.1a Unit overview: research themes

Research activity within both Mathematics and Statistics is structured around research themes or groupings, reflecting the breadth of activity within the unit and fostering the development of research communities, e.g. via reading groups and seminars, many of which have continued online in 2020. Many staff are affiliated with two or more groupings. In Mathematics for example, there is no sharp boundary between pure and applied analysis or between modelling and fluids, or financial mathematics and probability; and staff in Statistics typically affiliate with several groupings, reflecting the strong connections between branches of the subject.

The following paragraphs summarise the groupings, with key developments during the submission period. As an indicative measure of capacity, FTE headcounts are given as of 31st July 2020: these headcounts are numbers of returned staff affiliated with each grouping (in Statistics staff belong to multiple groupings).

Analysis and Combinatorics (Mathematics, 11.5 FTE). The addition of **Galkowski** and **Hadzic** (both awarded EPSRC fellowships within their first year at UCL) has broadened and strengthened the group in microlocal analysis and nonlinear PDEs, while the appointments of **Lee** (IMSS fellow), **Letzter** (Royal Society URF) and **Pokrovskiy** have created a critical mass in combinatorics, joining **Sokal** (EPSRC established fellowship from 2016), **Barany** (Szechenyi Prize of the Hungarian Government, 2016) and **Talbot**. Enumerative combinatorics has a particularly active visitor programme, with 5 long-term visitors (3-24 months) since 2017.

Applied Analysis (Mathematics, 7 FTE). This group has been strengthened by the addition of **Cooper** and **Zatorska** and recognised with the 2019 Calderon Prize to **Oksanen**.

Numerical Analysis & Scientific Computing (Mathematics, 5 FTE). Since the appointment of **Burman** in 2013 this has reached critical mass, adding **Hewett & Smears**, both Early Career Researchers (ECRs) but high-profile for their career stage: Smears won the Leslie Fox Prize of the IMA for his doctoral work at Oxford and has given keynote talks at several international conferences. The group is now highly active with 7 live research grants at July 2020, wide take up of **Betcke**'s Bempp and **Burman**'s Cutfemlib software, and many plenary invitations (**Burman**). In addition, Burman's team holds Associate Team status with the COMMEDIA team (INRIA, Paris).

CORU (Mathematics, 4.5 FTE) is undergoing a period of strategic expansion, starting with the appointment of **Crowe** (2016) followed by **Javarone** and **Diaz de la O** (2019). The group's work at the interface of Operational Research and Public Health Policy has been recognised by the OR Society through the award of the 2014 Goodeve Medal to **Crowe** and **Utley**, and the 2019 Lyn Thomas Medal to **Crowe**, **Pagel** and **Utley**. **Pagel** joined independent SAGE in May 2020 and has a high media profile for her expertise on the COVID-19 pandemic. The group's research awards amount to nearly £3.5M over the REF period.

Fluid Dynamics (Mathematics, 9 FTE). The group, which includes critical mass (**E Johnson**, **McDonald**, **Esler**) in Geophysical Fluid Dynamics, has remained relatively stable, with one new

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appointment in 2019 (**Hewitt**). The 2019 British Society of Rheology Annual Award went to **Wilson**; and **Vanden-Broeck** was awarded the Chaire Montel of the University of Nice (2019). Over the period, group members have given approximately 10 keynote / plenary lectures.

Geometry and Topology (Mathematics, 7 FTE). New academic appointments are **Beraldo** and **Bellettini**, also two new fellowship holders, **Foscolo** and **Segal**. The group continues its leading role in PhD training through the LSGNT (PI **Singer**) as noted above. **Louder** won the G de B Robinson Prize of the Canadian Mathematical Society for his 2019 paper (joint with Wilton) *Stackings and the W-cycle conjecture*. The Annals paper of **Foscolo** (joint with Haskins) is a landmark in the subject, giving exotic nearly-Kaehler structures and hence new examples of compact positive Einstein manifolds in 6 dimensions.

Number Theory (Mathematics, 9.4 FTE). The group has been strengthened by the appointment of **Granville** in 2015 and **Dokchitser**, **Garcia Martinez** and **Petrow** in 2019. The group's strength is reflected in the five fellowships / large ERC grants (1 URF, 4 ERC) that it has secured during the period. **Granville** won the 2019 Halmos-Ford Award of the Mathematical Association of America, while **Zerbes** shared a 2015 Junior Whitehead Prize and a 2015 Philip Leverhulme prize (both with Loeffler) for a major breakthrough in the theory of Euler systems. The group hosts two Heilbronn Postdoctoral Fellows (**Birkbeck**, **Lamplugh**) who are included as category A staff as independent researchers.

Financial Mathematics (Mathematics, 5 FTE). This group was strengthened by the addition of **Ni** and **Schwarz** in 2016. **Macrina** has strong industrial links (including funded collaborations with Opengamma and Winton Capital in the period); **Ni** is Co-I on an EPSRC programme grant (total value £4.1M) and is a fellow of the Alan Turing Institute.

Modelling (Mathematics, 5.6 FTE). This grouping consists of researchers whose mathematical expertise is principally a tool to address applications. Application areas range from traditional industrial mathematics (e.g. **Ovenden's** \$300k acoustics project with Arizona Department of Transport and company Illingworth-Rodkin, **Smith's** Impact Case Study with AeroTex), via society, healthcare and medicine, to biology (**Page** joined by **Manhart** in 2019).

Biostatistics (Statistics, 8.8 FTE) was established by **Omar** in 2007 with five years of funding from the NIHR UCLH/UCL Biomedical Research Centre, subsequently renewed twice (2012-2017, 2017-2022). The initial funded group has become a broader hub for biostatistics activity, enhanced with further departmental appointments (**O'Keeffe**, **Pavlou**, **Bartlett** – the latter two both ECRs, with **Bartlett** on an MRC Fellowship). **Omar** is the statistical lead for the UCL PRIMENT Clinical Trials Unit (collaboration with the Department of Primary Care and Population Health and the Division of Psychiatry) and an advisor to the National Institute of Cardiovascular Outcomes Research; she also contributed to UCL's research integrity policy document, which has informed the approval process for medical research projects from the UCL/UCLH Joint Research Office. **Baio** gave two keynote lectures over the period and serves the UK National Institute for Health and Care Excellence (NICE) as Scientific Advisor.

Computational Statistics (Statistics, 11.3 FTE) is a key strength, particularly in Bayesian computation. New ECR appointments include **Briol** and **Livingstone**, while **Dellaportas** and **Griffin** joined as Professors. Highlights include a Leverhulme prize (**Beskos**, 2014), an Amazon Research Award (**Briol**, 2019) as well as multiple plenary and keynote lectures (e.g. **Manolopoulou**, **Dellaportas**, **Silva**).

Economics, Finance and Business (Statistics, 7 FTE). This grouping has emerged since REF2014, partly in response to interest from industry in academic partnerships around data science. The

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grouping has a good track record of securing industry-sponsored research studentships (e.g. **Manolopoulou, Dellaportas**), and **Maier** was appointed as an ECR in this area in 2020. **Siddiqui** gave four keynote lectures, and **Griffin** has instigated research connections with UCL Economics by co-organising joint seminars to explore areas of mutual interest.

General Theory and Methodology (Statistics, 17 FTE). The size of the grouping reflects a broad interest in fundamental statistical methodology, including among those with application-motivated research. **Sadeghi** was appointed in 2018 as an ECR; he has already been appointed to the editorial board of the highly-regarded *Scandinavian Journal of Statistics*. The grouping has also recently benefited from a strategic expansion of expertise in probability, with two hires in 2019-2020 (**Soo, Watson**) to build with **Cotar** a very active probability group which, since January 2020, has been collaborating with Mathematics staff (**Sidorova, Macrina, Garcia Trillos**) via a weekly reading group with international guest speakers.

Multivariate and High Dimensional Data (Statistics, 9.3 FTE). Hires in this area include **Wang**, an ECR who was the recipient of the 2019 Royal Statistical Society prize. Other successes during the period include **Olhede's** £1M of EU funding to support projects on oceanographic data analysis (FP7) and *Networks in Time and Space* (Horizon 2020); and **Fearn's** election to the presidency of the International Council of NIR Spectroscopy (2017-2021).

Stochastic Modelling of Complex Systems (Statistics, 10 FTE). This is distinct from the *General Theory and Methodology* grouping in focusing on a broader class of (stochastic and non-statistical) modelling problems. In this area, **Chandler** gave two keynote lectures and led a £2M NERC consortium grant (2012-2016, UCL component NE/J017434/1) on *Probability, Uncertainty and Risk for the Environment*. **Guillas** has led two GCRF projects funded by NERC/ESRC/AHRC and Research England; he also hosted a Royal Society Newton fellow on a project relating to tsunami risk.

Beyond the two main departments, the Gatsby Unit research encompasses theoretical and computational neuroscience, computational statistics, machine learning and artificial intelligence. About two-thirds of its PhD and postdoctoral trainees have established successful academic careers, whilst others continue their research in companies such as DeepMind, itself founded by two former Gatsby fellows. The CSML centre was selected in June 2020 as a unit of the prestigious **European Laboratory for Learning and Intelligent Systems** (ELLIS) network, which aims to perform fundamental research in modern AI, attract top international industry research labs, and spawn start-ups that will become major players in the future. Membership of ELLIS also gives UCL access to its highly attractive **European PhD program**, aiming to retain the best graduates and transform them into the next generation of senior scientists.

Finally, UCL Mathematical Sciences is closely involved with the Alan Turing Institute. There are currently eight funded Turing fellows across the unit (**Beskos, Bishop, Dellaportas, Guillas, Manolopoulou, Ni, Silva, Xue**). In addition to several funded Turing projects (**Ni, Guillas, Dellaportas**), **Guillas** holds a 100% Group Leader Turing fellowship and also leads the Turing-wide Uncertainty Quantification interest group. Further funding for e.g. workshops and hackathons enhances the depth, breadth, and reach of the Data Science and AI activities across the unit.

1.2 Review of REF2014 Research Strategy

Our strategy for the period had eight strands: here we briefly review our achievements against each.

1. **Foster leadership in discipline-based research** through both recruitment and development of current staff, with a focus on quality over quantity. Our success in this

regard can be measured in part by our success in *externally-funded research fellowships* at all career stages: over the reporting period, there have been 5 EPSRC doctoral prizes; 5 EPSRC fellowships (**Hadzic, Oksanen, Olhede, Sokal, Wolfe**); 3 Royal Society URFs (**Dokchitser, Foscolo, Letzter**); 5 ERC Grants (**Granville, Olhede, Segal, Yafaev, Zerbes**); 2 Heilbronn fellows (**Birkbeck, Lamplugh**); one MRC Fellow (**Bartlett**, subsequently appointed to lectureship); one Royal Society Newton fellow (Gopinathan, host **Guillas**) and a *Biometrika* fellow (**Fernandez Aguilar**). Finally, **Granville** and **Wolfe** held Royal Society/Wolfson research merit awards.

2. **Continue and enhance interdisciplinary research.** There are many different interdisciplinary successes over the period; one to highlight is our investment in the UCL Centre for Inverse Problems, within which **Oksanen** was awarded the 2019 Calderon Prize (see Section 1.1a). Another is the Met Office Academic Partnership (see Section 1.1), instigated in 2020 with a major focus on data science, machine learning, uncertainty quantification and mathematical modelling.
3. **Increase PhD student numbers and improve gender balance.** Our PhD student numbers have increased steadily from 14 graduations per year in 2014 to over 20 per year in 2020; and the gender balance of the intake has improved from 32% female at the beginning of the period to 38% female now.
4. **Recruit excellent ECR staff.** Our unit has grown by 49.5% FTE in the period, and the majority of these new hires have been ECRs. Their excellence shines through: permanent academics **Bartlett, Fernandez Aguilar, Foscolo, Letzter** and **Segal** were all ECR at the time of award of their funding in point 1 above. In 2019 alone, **Wang** received the most prestigious award for an ECR in Statistics in the UK (the Royal Statistical Society Prize); **Pokrovskiy**, the European Prize in Combinatorics; and **Briol**, an Amazon Research Award (one of only 51 awards worldwide for outstanding, innovative research proposals across machine learning, robotics, operations research and related disciplines).
5. **Attract and foster career development of leading ECRs via the Clifford Fellowship.** The Clifford Fellowship is a departmentally-funded independent research post in Mathematics. The inaugural fellow, **Guerberoff**, now works in industry; the second fellow, **Perez Carrasco**, is a lecturer at Imperial; and we have just recruited the third fellow, **Kurnosov**. We have expanded on the success of the scheme to add *IMSS Fellows* across the unit: two (**Lee, Louca**) are now in post and this scheme will expand further (Section 1.3b).
6. The **Institute for Mathematical and Statistical Sciences** (see Section 1.1) was in the early planning phase in REF2014. This initiative to co-locate all groups in the unit to form a focal point for the mathematical sciences in London has now seen significant institutional investments towards its progress (Section 3).
7. We aimed to **strengthen our visitor programme** using new space in the IMSS. We have gained some space in Mathematics (see Section 3.2), but this remains a constraint that has limited our visitor programme expansion. This remains a key priority for IMSS.
8. **Increase total value of research funding and the amount from non-EPSRC sources.** Our research income has grown from £1.35M per year at REF2014 to £4M per year in the current period, and now includes £2.5M per year from non-EPSRC sources. Section 3.1 gives more details.

1.3 Ongoing Research Strategy

As described in Section 1.1, UCL is currently investing significantly in a major expansion of the mathematical sciences, working towards the establishment of the **Institute for Mathematical and Statistical Sciences (IMSS)**. This investment recognises the rapid expansion of opportunities for

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the mathematical sciences nationally and internationally, evidenced for example by the government's doubling of funding for the EPSRC Mathematical Sciences programme early in 2020, and by the increasing demand for taught mathematics and statistics degrees from exceptionally qualified candidates (numbers of applications to our undergraduate programmes increased from 2572 in 2014/15 to 4263 in 2019/20; and postgraduate taught applications increased from 1180 to 2683 over the same period). Our undergraduate students achieve exceptional things: in 2020 a Mathematics student was awarded a first prize in the International Mathematics Competition for University Students, while in 2018 a Statistics student was in the winning team for the \$1 million global Hult prize.

The key points in the IMSS expansion strategy are (i) recruitment of excellent academic staff, at all levels but with a particular emphasis on ECRs who will be the research leaders of the future; (ii) provision of support for staff to develop their careers and fulfil their potential; (iii) incentives for major research initiatives; (iv) better integrating the mathematical sciences community across the institution; (v) capacity-building in key areas (including dedicated professional services support) so as to be able to respond to emerging opportunities; and (vi) engagement with researchers in other disciplines and with external organisations, as a route to impact for our research. The first two of these points are discussed in Section 2 below. Strategy for the remainder is as follows.

1.3a Incentivising research activity

We will continue increasing the volume of research activity and income within the unit. The average annual research income per FTE submitted has more than doubled since REF2014 (see Section 3.1), but there is scope to increase this still further, particularly in the current funding climate. The strategy for achieving this is threefold: *increase the time available for research*; *provide support and feedback* to those preparing research grant applications; and *provide incentives* to reward the effort that goes into preparing large bids.

Increasing the availability of research time is most easily achieved by ensuring that staff numbers increase more rapidly than other commitments: this is built-in to the IMSS timeline. We have, moreover, invested in additional support for meeting our teaching commitments (see Section 2), thereby reducing the teaching and administrative burdens on research-active staff.

At departmental level, structured *support for research grant applications* includes systematic internal reviews by each department's Research Committee. For larger cross-departmental or cross-institutional bids, as well as fellowships, strategic facilitators from the Office of the Vice-Provost (Research) provide support in the form of meetings, gathering of expertise, case reviews and mock interviews. For example, in 2019 the team organised a new workshop on grant funding in Statistics, with concrete outcomes in terms of success rates: in the three years prior to July 2019, 25 of 75 Statistics proposals were successful for a total value of £1.5M while, of 12 proposals in the subsequent 12-month period whose outcomes are known, 10 were successful for a total value of £1.2M, including a three-year EPSRC award to ECR **Wang**.

This support for research grant applications is complemented by a *research grant incentive scheme*. It provides discretionary funds (around 0.5% of the amount sought) to applicants who bid for more than £100k and has led to a boost in grant applications and several recipients. Statistics also adopted in 2019 a scheme that awards a PhD studentship whenever an application exceeds 30% in overheads after removing the studentship costs. This institutional commitment has already increased the number (and value-for-money) of larger bids, typically above £300k. Mathematics

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typically has fewer funders who do not pay overheads; but large grants are routinely incentivised with PhD studentships to increase the value for money to the funder.

1.3b Mathematical sciences research community

The physical separation of Mathematics and Statistics at UCL has historically inhibited natural collaborations between the disciplines. A key part of the IMSS vision is, by bringing the departments closer together physically, to create a large and vibrant mathematical sciences community within the institution: this in turn will enable us to build on existing collaborations and to exploit research synergies more effectively. Substantial progress has already been made in this direction, with high-profile active collaborations emerging since REF2014 as well as events that highlight the breadth of mathematical sciences activity. Examples include the cross-department collaboration in probability (see Section 1.1a); the cross-departmental *Women in Mathematical Sciences Network* (Section 2.4); and an internal “IMSS academic launch” symposium held in January 2020.

To develop the research community further over the coming period, several initiatives are in place:

- *IMSS Fellowship scheme*. Following on from point 5 of the REF2014 strategy, we have instigated a rolling programme of internally-funded three-year research fellowships (see Section 2 below), with two fellows appointed during the inaugural year of the scheme in 2020 and two further fellows appointed annually thereafter. From 2022 onwards there will be three IMSS fellows in each department at any time, who, in addition to developing their own independent research programmes, will form a key link between the departments (e.g. they will be co-located in the same office space) and who will be able to help with the organisation of joint internal and external events.
- *Event management support*. The departments will pool resources to recruit an IMSS event manager. Together with a refurbished building equipped with meeting spaces and collaboration facilities, this will increase our capacity to host national and international meetings, conferences and workshops in the mathematical sciences – including with involvement from learned societies in our disciplines.
- *Research student community*. There are opportunities to increase interactions between the research student communities in the two departments, for example by coordinating training and skills development activities. The 2020 increase in EPSRC Mathematical Sciences funding will enable us to substantially increase the volume of activity funded through a **Doctoral Training Partnership** dedicated to the mathematical sciences at UCL; and we plan to augment this with additional funding streams, for example with industry-funded studentships capitalising on the current surge of interest in data science (see Section 2.3 for more on existing industry-funded studentships).
- *Research visitor programme*. An active visitor programme will build and maintain links with the UK and international community and will contribute to the calendar of IMSS events. This visitor programme will be enabled via the move to premises equipped with office space for visitors, as well as space for collaboration.

1.3c Capacity-building in key areas

At a national level, the uplift in Mathematical Sciences funding reflects a broader recognition of the discipline’s importance, as exemplified by the 2018 Bond review. We are keen to take advantage of the resulting opportunities and have already started to develop capacity in key areas such as Data Science (e.g., via our engagement with the Turing Institute) and mathematics for healthcare (e.g., via the strategic expansion of CORU – see Section 1.1). The expansion of CORU, in particular, has enabled staff to respond with agility to the demands of the COVID-19 situation,

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supporting several local hospitals in their COVID response resource planning and outcomes analysis and helping set up quality control systems at the London Nightingale hospital. Over the next few years, we aim to increase our capacity further in these areas, and to move with developments in the subject as part of our continuing expansion. Section 2.1 provides more details.

1.3d Engagement with other disciplines and external organisations

With critical mass in both fundamental and applied mathematical sciences research, the unit maintains an extensive network of interdisciplinary collaborations both within and beyond UCL, including joint appointments and partnerships led from within the unit. These collaborations provide opportunities for research contributions into other disciplines, as well as a route to impact for mathematical sciences research.

Over the coming period we will build on our existing networks to increase our capacity for interdisciplinary engagement. Within UCL this will be achieved via further strategic joint appointments with other departments as part of the IMSS expansion, as well as workshops and events designed to identify opportunities for fruitful collaboration: this will lead ultimately to increases in joint activity and research funding. We will also capitalise further on opportunities from industry and government, in particular by appointing an Industry Liaison Coordinator to liaise with external partners: this dedicated support will bolster our capacity for such partnerships, and hence offer enhanced opportunities for impact. We will continue to make full use of schemes such as EPSRC Impact Acceleration Awards and Knowledge Transfer Partnerships; and we will introduce an *impact incentive scheme* to encourage staff to carry out and evidence impact-generating research. Like the research grant incentive scheme described above, this will allocate discretionary funds to all contributors of Impact Case Studies to the next REF exercise.

More details of collaborative research and impact-generating activities are given in Section 4.

2. People

2.1 Staffing strategy

We have pursued a strategy of research growth throughout the period, thanks to a sustained commitment from UCL. This has allowed the creation of a large number of posts with the ambition of: (1) reducing the student/staff ratio in the departments to provide more research time and to improve the student experience; (2) supporting the creation of IMSS as an internationally prominent centre for the mathematical sciences at UCL which will compete with the best worldwide in terms of research, facilities, exchanges, interactions and leadership. As a result, our growth has been 50% FTE from REF2014, including the two newly created independent IMSS fellowships in 2020.

Our expansion strategy has been to invest in staff at a range of career stages, and to support them on arrival. We have sponsored independent research fellows, supporting the health of the discipline by recruiting the next generation of leaders. Our permanent academic posts attract high-quality researchers: amongst our recent appointments, six had independent research fellowships or ERC grants at or near the time of appointment (**Dokchitser**, **Hadzic** and **Segal** and ECRs **Bartlett**, **Foscolo** and **Letzter**). **Galkowski**, appointed in 2019, was awarded an EPSRC early-career fellowship in 2020.

When recruiting staff, our first priority is excellence – and we have been very successful in recruiting excellent staff during the period (see evidence above). When advertising vacancies at all career stages therefore, posts are usually advertised to the broadest possible field. However, as a

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large centre for the mathematical sciences, our ethos is that a healthy and functional mathematical research community requires both a critical mass of expertise across all major areas as represented by our research groupings, and an ability to evolve with current developments in the discipline. Where necessary therefore, we have carried out targeted recruitments: examples include the two posts (**Diaz de la O, Javarone**) committed to CORU in 2019 as a strategic investment in one of our most impactful groups. In Statistics moreover, applications are routinely encouraged from those with expertise and interests in current priority areas.

During the review period, the net effect of this staffing strategy has been to strengthen existing groups (e.g. **Dokchitser, Petrow, Garcia** in Number Theory; **Soo, Watson, Garcia Trillos** in Probability) and to bridge between groups (e.g. **Galkowski** bridging between Analysis and Geometry; **Griffin** bridging between Computational Statistics and Economics). We have also recently amended our appointment criteria to include the potential impact of candidates' research.

We entered the period having just set up the **Clifford Fellowship**, a departmentally-funded independent research post in Mathematics. This three-year post has been filled twice more (alternating between pure and applied mathematics, currently held by **Kurnosov**), and with additional institutional support we have supplemented it with two three-year **IMSS Research Fellowships (Lee, Louca)**. This strategy of supporting the very best researchers to kick-start their independent research careers will be continued, expanding to a rolling programme with three IMSS Fellows based in each department at any one time.

We have made occasional strategic appointments at professorial level (**Granville, Dokchitser, Griffin**) to feed critical mass in key research areas and maintain a balanced profile in terms of experience and leadership, allowing us to provide expert support to our ECRs. But the majority of our appointments have been at the ECR stage, where our staffing strategy has been particularly successful in recruiting outstanding researchers. For instance, since 2017 we hired staff from several top-ranked UK and international Universities: Cambridge (**Briol, Hewitt, Letzter, Sadeghi, Wang**), Oxford (**Beraldo, Fernandez Aguilar**), Columbia, USA (**Orbanz**), Northeastern, USA (**Galkowski**), ETHZ, Switzerland (**Petrow**), EPFL, Switzerland (**Maier**), Toronto, Canada (**Garcia**), Bristol (**Livingstone**), Manchester (**Watson**) and Imperial College (**Manhart**).

Our growth has always been supported financially by our ability to recruit and teach large numbers of highly qualified undergraduate students, but this does come with associated workload. To alleviate this, both departments have invested strategically in *Lecturers (Teaching)* during the period. These are staff whose expertise and interests are recognised as primarily teaching-focused but who nonetheless have a career and promotions pathway to professorship (separate from academic staff active in disciplinary research) and who are expected to carry out pedagogical research. By increasing their numbers substantially (to 11 FTE across the two departments during the review period), we have increased our capacity to deliver excellent teaching and support to our students, while simultaneously freeing up research time for other academic staff. Our teaching-pathway appointments have also enabled us to relieve research-active academics of various heavy teaching-related tasks and administrative duties (in Statistics, Chair of the Exam Board, Director of Studies, Athena SWAN chair and Departmental Tutor; in Mathematics, deputy exam board chair, Athena SWAN co-chair and E-Learning Champion; these roles were all held by research-active academics in REF2014).

2.2 Staff development

New academic staff have an induction process which includes training in a range of areas including safety, research supervision, and grant writing, as well as teaching, and equality and diversity. Experienced academics have a 12-month probation period, while academics without extensive

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teaching experience have 36 months. The probation period includes careful mentoring and appraisal; no academic staff have failed probation in either department in the period. New academic staff are supported through light teaching and administrative loads in their early years.

Since 2018, new hires in Statistics are given a research start-up fund of £6k. In Mathematics the process is less formal, but those who have arrived too recently to have been able to bring in funding are supported with generous departmental travel support. This support reduces the need to scramble for funding to go to conferences or invite research collaborators for visits, and allows initial small steps that bear fruit later. Recipients of the funding have used it to visit collaborators, leading to grant proposals and joint paper submissions; and also for dissemination at high-profile international conferences with publications in the associated proceedings.

The formal route for the support and development of established academic staff in both departments is via the mentoring and appraisal systems. In 2016 Statistics produced guidelines for conducting appraisals in order to ensure: (1) that the appraisal process is constructive, effective and supportive (2) uniformity of appraisal experience regardless of who is carrying out the appraisal. Mathematics is now adopting this good practice.

Each department has a Promotions Committee, set up to create an environment in which all academic staff are encouraged and supported in their career and promotion aspirations. These committees meet annually and consider all non-professorial staff against UCL's Academic Careers Framework: those who are not yet considered ready for promotion are given advice on how to progress, while others are actively encouraged to apply for promotion even if they were not planning to.

Sabbaticals are advertised on an annual cycle: requests are evaluated against criteria including the planned research activity, previous teaching loads, and EDI considerations. Specific sabbatical leave is available following major administrative roles (e.g., **Petridis**, Former Chair of Mathematics Teaching Committee, sabbatical 2016-17; **McDonald**, former Mathematics HoD, sabbatical 2018-19) and after extended parental or carer's leave. Our take-up of sabbatical leave has increased during 2014-2020 (from two staff members in 2013-14 to eight in 2019-20). We encourage staff on sabbatical to take international opportunities when they arise: for example, **Lotay**, **Schulze** and **Singer** were all research or Eisenbud professors at the MSRI special semester on differential geometry in spring 2016; **Xue** was based at Tsinghua University in China from 10/2019 to 2/2020; **Besos** was based at the National University of Singapore from 1/2020 to 6/2020; **Pagel** held a Harkness Fellowship in the USA in 2016-17, and in 2019 **Galkowski** spent his first term of UCL employment as a research member at MSRI for the microlocal analysis program on which **Singer** was also a research professor. We regularly give sabbaticals or rearrange teaching to accommodate attendance at INI meetings.

Across the unit, staff are supported in their research grant applications by receiving advice and feedback on proposals from mentors, holding mock interviews and by support from the professional services. Section 1.3 provides more details.

Participation in external committees is encouraged and given due credit in the appraisal and, especially, the promotion systems. Major commitments are taken into account when assigning departmental workloads.

2.3 Research students

2.3a Funding streams

PhD students are the lifeblood of the discipline. For this reason, in addition to external funding from a wide range of sources, we have invested in departmentally-funded PhD studentships (increasing

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across the period, now 7 per year in Mathematics and 2-3 per year in Statistics). This investment is one of the major reasons that our PhD numbers have increased during the period, almost doubling in Mathematics between January 2013 and January 2020 (see Section 1.1). We have prioritised new hires in our allocation of PhD funding, and some of these new hires have built research groups of up to four PhD students. When an ECR is acting as primary supervisor to a research student, both the student and supervisor are supported by an experienced staff member within the supervisory team.

We benefit from many sources of institutional, national and international sources of research student funding, allowing us to recruit top students from all over the world. Schemes include the UCL Graduate Research Scholarship and Overseas Research Scholarship (11 such scholarships in the unit over the period). Many fully funded external fellowships have supported top international students thanks to Governments and Foundations from Korea, Taiwan, Brazil, Turkey, Mexico, and the Commonwealth Scholarship Commission. Some schemes such as the Impact scholarships (10 awards) or overseas schemes (Chinese Scholarship Council 4 awards, Singapore AIST 3 awards, Japan JAIST one award) require 50% co-funding for fees or stipend from UCL: this has been provided in all cases during the period.

The **EPSRC CDT in Geometry & Number Theory (LSGNT)** with initial EPSRC funding of £4.7M in 2014 was renewed in 2019 (£6M). This is the only CDT in the country in pure mathematics and is a major collaboration led by UCL, with King's and Imperial as equal partners. Cohorts typically consist of 16-18 students, based at UCL in their first year and subsequently shared between the partners. The CDT also accommodates aligned students and has caused a step-change in the quality and numbers of PhD students in the unit in these research areas (accounting for an intake of 36 UCL PhD students in the period, including aligned students). The Heilbronn Institute contributes 50% funding for one studentship in each cohort.

The **EPSRC CDT in Foundational AI** is 50% industry-funded. It funds research students focusing on Statistics for AI and machine learning. It is hosted in Computer Science, and supported two students in Statistics during its first cohort starting in 2019.

The **EPSRC CDT in Financial Computing and Analytics** (based in the Computer Science Department at UCL) supported 4 PhD students over the period.

From 2020 UCL is a partner in the cross-institutional **Health Data Research UK-Turing Wellcome PhD Programme in Health Data Science**, which aims to develop future leaders in health data science.

As well as these large, formal links with Computer Science and the Alan Turing Institute, we jointly supervise research students with many disciplines, departments and institutes across UCL: in the medical field alone we have collaborated with the Cancer Institute; Institute of Child Health; Institute of Women's Health; Institute of Neurology; Institute of Clinical Trials and Methodology; Eastman Dental Institute; and Departments of Surgery & Interventional Science, Medical Physics and Psychiatry. Other supervision partnerships have involved the School of Management; Geography; Security & Crime Science; London Centre for Nanotechnology; Space & Climate Physics; Epidemiology; Psychology & Language Sciences; Biosciences; Molecular & Cell Biology; Epidemiology; Chemistry and many departments in the Faculty of Engineering. These interdisciplinary projects enable students to bring their mathematical expertise to a wide range of application areas, as well as enabling students from other disciplines to acquire modern

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mathematical skill sets; they also provide routes towards further research funding, influence and impact.

Staff in the unit also jointly supervise with several industry and government partners including AWE (1), Shell (1), MAPI group (1), Winton Capital Management (1), UK Met Office (2), and GCHQ (several students via the Heilbronn Institute and the LSGNT). Other industrial partnerships, involving (for example) in-kind support and funded internships, come from Avon Protection, Aerotex, GSK and others.

2.3b Student support and development

Our PhD students are each provided a funding stream to bid for training and conference attendance (around £1000 per year), irrespective of their funding source. We also ensure that supervisors have time to provide high-quality advice for each of their students by explicitly recognising PhD supervision in the workload (48 hours per year per student in Statistics), up to the UCL maximum limit of six PhD students per staff member.

Statistics has set up a mentoring scheme for all PhD students: a primary aim of this is to provide access to personal advice on career development. Mathematics offers PhD students annual panels run by postdocs about postdoctoral research, and mock interviews for postdoctoral posts. There is a dedicated mentor to those PhD students who are Teaching Assistants, along with discipline-specific bespoke training provided by the UCL Institute of Education. In addition, **Hewett** leads annual PhD student training days (attended by over 60 students since their inception in 2018) which aim to: empower students to take ownership of their PhD projects; introduce practical tools for time management and objective setting; advise on how to get the most out of their supervisory relationship; provide guidance on how to navigate conferences, seminars and workshops; and encourage professional profile development. These training days have also incorporated careers fora with academic and industrial panel members.

All our PhD students have the opportunity to attend courses at the **London Taught Course Centre (LTCC)**, which involves a consortium of universities from London and the South-East. Originally EPSRC-funded but now self-sustaining, it offers courses across the remit of the mathematical sciences. Basic courses are designed for first-year students, who should take three or four to broaden their mathematical outlook. Intensive courses are focused on a single topic, and tend to attract students whose research is directly related to the topic. UCL supports the LTCC through academic staff contributions (**Halburd** is currently director and many staff have taught courses in the period) and through administrative support. In addition to this, students requiring advanced computational skills benefit from the training offered by UCL's Research Software Development group (Section 3.3).

Our PhD student community is very active beyond the students' individual research projects. The students produce *Chalkdust* (a magazine for the mathematically curious), which comes out twice a year and has a circulation of 60,000 as hard copies alone and an active web presence; and members of the LSGNT have formed *London Maths Outreach*, which offers weekly mathematics enrichment activities for London schools.

2.3c Research student success

We have graduated 159 research students during the period, of whom 140 were primarily supervised by staff within the unit and the remainder were co-supervisions with other units. The achievements of our students, building on their excellence and our training, are really world class, as seen by international awards such as one of only 24 recipients of the 2020 IMS Hannan Travel Award worldwide, the 2018 Lee B. Lusted Student Prize (Society for Medical Decision Making,

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European Conference First Place), the “best student presentation” prize at the 2018 International Workshop on Statistical Modelling, and the selection of some of our students for fully-funded attendance at very selective training such as the Machine Learning Summer School 2020 (only 180 students selected worldwide). National and local recognition includes the Vernon Harrison Doctoral Award (2017), and two separate instances (2014 and 2015) of the UCL MAPS Faculty Postgraduate Research Prize.

Around 90% of the Gatsby Computational Neuroscience Unit former PhD students and postdoctoral fellows work in a scientific or academic setting, with over 60% going on to academic positions in universities or research institutes and almost 30% working in a research setting in companies such as DeepMind (itself founded by two former postdocs). Two won the Eric Kandel Young Neuroscientist Prize in 2015 and 2019.

Immediate destinations of former PhD students in the unit include postdoctoral research fellowships at the Universities of Toronto, Cambridge, Oxford and at the European Bioinformatics Institute. In 2016-17 three of our PhD graduates were recipients of LMS 150th Anniversary Postdoctoral Mobility Grants (held at Imperial, Bristol and Copenhagen (Denmark)). Others have gone on to postdoctoral roles at a wide range of institutions nationally and internationally, including Shanghai Tech (China), Taipei (Taiwan), Laval (Canada), IHES (France) and the Institute of Advanced Study (USA). Several more have gone to permanent academic posts either immediately, or after postdoctoral positions – permanent destinations in the UK include Bath, Durham, Lancaster, Portsmouth, and Reading; and worldwide, at the Universities of Bordeaux, Toronto, Maastricht, Melbourne, Politecnico di Milano, Ocean University (China) and the National University of Singapore. One PhD graduate has become the Head of the Department of Biostatistics at Bolu Abant Izzet Baysal University (Turkey); another is a permanent research scientist at National Oceanic & Atmospheric Administration, (USA); and yet another was recruited to the editorial board of the international journal *Trials* immediately after the publication of the first paper from her PhD thesis. Beyond academia, we have many PhD graduates now holding prominent posts in industry, including Chief Data Scientist at PeerSourcing Solutions (USA), Data Scientist Consultant at QuantumBlack (London), Principal Statistician at GlaxoSmithKline, Senior Principal Modeller at Risk Management Solutions (London), and Research Scientist at Eigen Technologies (London).

2.4 Equality and diversity

An EDI focus and a commitment to a **welcoming and supportive research environment**, runs throughout our unit. Gender is a key issue – Mathematics and Statistics hold Athena SWAN Silver and Bronze awards, respectively – but is not the only area of attention. We are also keenly aware of the need to recruit and support both BAME and LGBTQ+ PhD students and staff in mathematical sciences since these groups are generally under-represented in STEM. We actively promote an inclusive culture, e.g. running events related to Black Mathematicians, talks and events celebrating International Women’s day, LGBTQ+ friendly socials, prominent display of ‘Friend of Out@UCL’ banners on office doors of senior staff, and organising ‘wikithons’ to write Wikipedia pages about mathematicians from under-represented groups.

UCL offers training entitled “Where do you draw the line?”, intended to foster an environment of zero tolerance for bullying and harassment, and a culture in which bystanders feel empowered to challenge inappropriate behaviour. Each department has been running annual sessions through the whole period, in the expectation that all staff should have attended one.

In our **recruitment of PhD students**, all staff involved in PhD recruiting or supervision have to undergo appropriate training. Staff are strongly encouraged to take advantage of at least three training opportunities per year, and this is monitored via the annual appraisal scheme. EDI

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initiatives include female membership on interview panels for female PhD applicants; social media with a focus on being welcoming and friendly; even gender distribution of paid summer UG internships; increased visibility of female role models (for example, a requirement for gender balance when inviting speaker suggestions for the Statistics seminar series); and participation in the *Mary Lister McCammon Summer Research Fellowship* led by Imperial College, a funded 10-week research programme for UG female finalists to work with a leading mathematician or statistician.

Our **PhD student support** described above is offered to all students regardless of background: nonetheless, we observe that good practice has a disproportionately strong effect on those who need it more. Some more tailored EDI support is provided by UCL's Black Doctoral Students' Network, that aims to connect all new and existing departmental research students: we support and encourage students to join the network if appropriate. In addition, the departments have female academic staff members in the role of mentor to female PhD students.

At the level of **staff recruitment**, all appointment panels are at least 1/3 female, and adverts are vetted for gendered language before publication. All roles are advertised as widely as possible to ensure visibility to a diverse range of applicants. As further evidence of our commitment to improved recruitment outcomes, Statistics immediately committed in 2018 (followed by Mathematics in 2020) to a UCL-wide "Fair Recruitment Specialist" initiative. Under this initiative, which is intended to address fairness relative to all protected characteristics, all shortlisting and interview panels include a trained recruitment specialist from UCL staff.

We **support our postdoctoral research staff** (the only fixed-term research staff in the departments) with central support to write fellowship proposals, and mock interviews for fellowships and academic jobs. Research staff are also assigned a mentor independent of their PI / line manager, to provide independent support and advice.

Our postdoctoral researchers often progress to permanent academic posts, including within the Unit (**Garcia Trillos, Crowe, Pavlou, O'Keeffe**) and at other strong mathematical departments around the UK (e.g. two postdocs who left in the period are now Zeeman lecturers at Warwick, with others taking up positions at Bath, Birkbeck, Loughborough and Royal Holloway) and further afield (Western University (Canada); University of Virginia (USA); Universidad Carlos III de Madrid (Spain); Erasmus University (Netherlands); Chinese Academy of Sciences). Still others take their mathematical expertise into other disciplines and sectors: e.g., Professor of Behavioural Science at Warwick Business School; Lecturer in Theoretical Systems Biology at Imperial College; Head of Solutions & Analytics Innovation, The ai Corporation.

The unit's policy of an automatic term of sabbatical leave following an extended period of parental or carers' leave, which has been in place since 2013 (**Wilson**) has now been implemented at institutional level. Our Promotions Committee good practice has also been observed to be effective at narrowing the gender pay gap: the action of encouraging individual staff to apply for promotion without their having to make the first move is a direct response to impostor syndrome, and though the overall numbers are small it is heartening to see that, though only 17% of our academic and research staff are female, 25% of the successful senior promotions across the period were female.

We also have specific actions related to gender. For several years, the two departments together have been running a *Women in Mathematical Sciences Network* which organises termly meetings: a typical format is a lecture from a woman scientist followed by a lunch. Both departments promote gender equality amongst speakers in departmental seminars. In Statistics, by 2018-2019 the proportion of female seminar speakers reached 47%, up from 5% in 2013-2014; in Mathematics the departmental colloquium series has been gender-balanced since 2018. Looking outwards

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rather than inwards, our research outreach activities also have a focus on gender (e.g. Impact Case Study from Hannah Fry & **Wilson**).

Both departments promote balanced gender representation on committees; in addition, Statistics rotates the membership of the Senior Management Team (SMT) with the aim of achieving a better balance. The role of HoD rotates on a 5-year timescale in both departments. We encourage participation in UCL's Women in Leadership programmes (**Wilson, Pagel, Ni**) and alumnae of these are successful in moving into leadership roles. **Wilson** is the first female HoD of Mathematics at UCL since its founding in 1827, and one of the few current female HoDs of Departments of Mathematics in the UK. Statistics had its first female HoD prior to the REF period (**Isham** in 1996). **Pagel** is the first female director of CORU, and deputy director **Crowe** is also female.

The majority of our staff can (and do) work flexibly, including working from home and working non-standard hours, so long as this does not interfere with the performance of their duties. We have committed not to schedule important meetings outside Core Hours (10.00-16.00) to allow for childcare responsibilities; and have encouraged seminar organisers to use lunch, rather than dinner, as the default time to entertain a guest speaker. During the period several staff have moved to part-time working for family reasons; when they have requested a return to a higher proportion of FTE this has always been granted. At Faculty level, we have recently set up a Carer's Fund, which provides funding to allow conference attendance and research travel for those whose caring responsibilities would otherwise prevent it. This has primarily been used for childcare cover, as well as covering care costs for vulnerable relatives while a staff member is away.

Our approach to **wellbeing** has been thrown sharply into focus by the COVID-19 pandemic. Since March 2020, we have instituted a range of online activities to help staff and students stay in touch, including random-group coffee meetings, buddy systems, and regular tea meetings. Coupled with more practical help (a faculty-level fund to assist with home-schooling, and generous departmental provision of extra equipment to make remote collaboration practical), these help our staff and students to feel valued as they work through difficult circumstances.

Over the period, our commitments to EDI are slowly paying off in our PhD intake: our latest intake was 38% female, increased from 32% female at the beginning of the period (and well above the sector average of 25%). The proportion of non-white students has also increased (from 32% to 46% across the period), as has the proportion of students disclosing a disability (though the numbers here are extremely small).

The selection of outputs towards our **REF submission** has been led by a team across the two departments. Each staff member was asked to nominate up to 5 outputs for consideration. These were then reviewed and scored by academic staff across our various areas of expertise, including ECRs. Specific EDI training relevant to the role was provided by the institution.

Following the institutional code of practice, we checked the profile of the initially selected outputs against a range of inclusiveness criteria. The profile of outputs against career stage is almost perfectly distributed: all age groups except the over 55s have outputs per FTE of 2.5. The profile of outputs by gender is also close to balanced (especially given the small numbers involved and the fact that several female staff have taken maternity leave in the period): the mean outputs per FTE are 2.5 and 2.4 for male and female staff respectively. The final submitted outputs have therefore not been adjusted in response to this review.

The selection of impact case studies (ICs) towards our **REF submission** has been led by a team across the two departments and the UCL-wide specialised team. Four out of seven ICs are

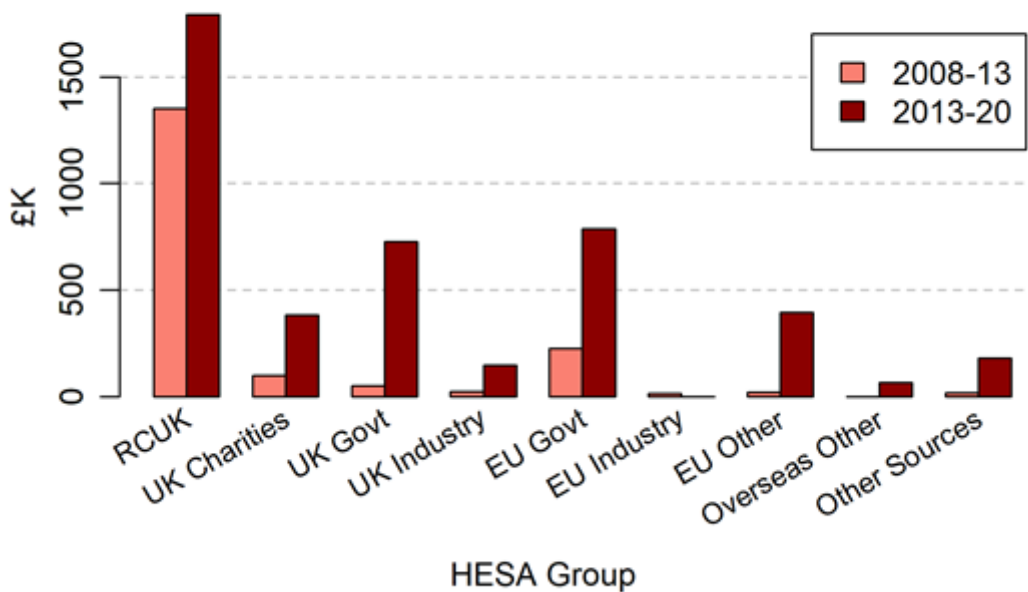
women-led or women-majority led 57%, and in terms of staff involved **60% of the ICSs contributors are women staff, well above our 17% female staff ratio.**

3. Income, infrastructure and facilities

3.1 Research income

Our research income has been transformed over the REF period: from £1.8M per year in the period covered by REF 2014, to £4M per year in the current period. Figure 1 shows that this expansion is driven not only by an increase in the volume of research funding, but also by a major diversification of our funding portfolio with notable increases in funding from UK government (including health authorities) and EU sources, and one joint NERC/NSF award (**E Johnson**). Highlights in the funding portfolio include the EPSRC fellowships and ERC grants noted in Section 1.2, of which six had award values above £800K (three above £1M); an EPSRC Programme Grant (Section 1.1) bringing £605K to **Ni** as Co-I; EPSRC award EP/P024793/1 to **Parnovski** for £520K; several large awards to CORU from healthcare organisations and agencies (two awards above £500K to **Crowe** and two to **Utley**, one of which secured funding of £830K from the Department of Health and Social Care to evaluate the pilot implementation of vaccinating healthy schoolchildren against seasonal influenza); and industry funding of £499K from MAPI / ICON to support **Baio**'s position and research programme. Elsewhere in the unit, the *Biostatistics* research group obtains grant funding as statistical lead and Co-investigator, for many collaborative health research projects: for example, in mid-2020 the UCL Medical School including the PRIMENT Clinical Trials Unit (involving **Omar, O'Keeffe, Pavlou, Baio**) were conducting more than 20 research studies, both in the UK and internationally, funded by the National Institute of Health Research, ESRC, the Wellcome Trust and the MRC.

Figure 1: Annual average value of research awards by funding source (HESA Group), 2008-2013 and 2013-2020.



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The increase and diversification of research funding is, of course, partly driven by the exceptional growth of our unit (+49.5% FTE). However, that growth does not tell the whole story: many of our colleagues are very recent hires who have had limited time to bring in funding (out of 94.15 FTE, 38 FTE (40.36%) joined since 2016 and 24 FTE since 2019). Nonetheless, after accounting for staff growth we still find a 50% increase in annual research income per FTE: to £47,584/year/FTE, from £28,594 in REF 2014. This is a major achievement and a testament to the success of our research strategy outlined above – for example the research incentives that have been introduced during the period, the start-up funding for new hires and the increased support for staff preparing large proposals. Looking to the future we anticipate that these initiatives, coupled with the ongoing expansion of academic staff numbers and professional services support (see Section 3.2), will increase this momentum still further.

It is worth noting here the success of our activities to support equality and diversity around research grant applications. While only 17% of our academic staff are female, they account for 25% of our research income over the period.

3.2 Infrastructure

Mathematical sciences research makes modest demands in terms of infrastructure. The main requirements are individual and collaborative space; access to the latest developments in the discipline via journals, conferences and other forms of dissemination; appropriate professional services support; and, in some areas, access to appropriate computing facilities.

In our central London location, space is at a premium. During the period, UCL has invested heavily in physical infrastructure in Mathematics. In a £3.8M project, the fourth floor of 25 Gordon Street was remodelled from its previous use for the Students' Union and repurposed to provide extra space for Mathematics. This new space provides 13 new academic offices and a shared PhD office which seats 20, along with associated seminar and meeting space.

Looking forward to the next seven years, the proposed IMSS (see Section 1.1) will create a bespoke building that is designed for 21st-century mathematics activity. The building will house individual offices for academic staff, purpose-built teaching and collaboration spaces, and also facilities for international seminars and workshops via videoconferencing. This will benefit the unit directly, and will allow UCL to position itself as a major London venue for events across all of the mathematical sciences.

UCL has outstanding library facilities, with an extensive physical collection (including the collection of the London Mathematical Society) as well as online access to over 50,000 e-journals including a comprehensive collection of mathematical sciences journals and e-books. Both departments have a generous annual budget for the purchase of new books and journal subscriptions. Funding for travel and conference attendance is also essential to ensure that staff can keep abreast of developments in the discipline and disseminate their work: both departments also have funds to which staff and research students can apply for support, therefore. Where necessary, priority for these funds is allocated to research students and ECRs.

The unit has also invested in professional services (PS) support during the period: the PS team in Mathematics increased from 9 FTE in 2013 to 13.5 FTE in 2020, while that in Statistics increased from 5.2 FTE to 9.7 FTE over the same period. Most of the new capacity was in the area of teaching support, thus transferring non-specialist administrative and teaching-related tasks from academics to PS staff and increasing the amount of academic staff time available for research. There are dedicated research support posts within both departments, for example, both departments have dedicated IT Systems Administrators with specialist expertise to support local research computing infrastructure (Section 3.3): Mathematics started the period with one such

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administrator and now has two. Moreover, in 2017 Statistics appointed a new full-time Finance and Research Administrator, whose responsibilities include providing support with research proposal costings as well as grant maintenance and support with research contracts. Finally, both departments receive additional PS support where needed from the teams at the MAPS faculty and (larger) school level – for example, with organising the outward-looking networking events described in Section 4.2.

3.3 Research computing

Each department has its own internal computer network, with all machines being accessible to departmental staff and research students from PCs or workstations in their offices, or remotely. We have backup servers, and remote storage: the departmental systems are maintained by dedicated Systems Administrators, as described above.

In Statistics, the internal network is based on a few fast Linux servers running a variety of commonly-used packages. For moderately intensive computations, researchers in the Department have access to a powerful internally-owned cluster.

In Mathematics, the Unix computing facilities comprise over 72 general purpose computing machines, alongside a dedicated 16 node Linux High Performance Computing (HPC) cluster having a total of 218 CPU, with Nvidia GPUs in many, and a high-speed network fabric. We have a high-performance machine with 2TB RAM for manipulation of polynomials (frequently multivariate) of very high degree with very large integer or rational coefficients, and a high-performance machine dedicated to machine learning (TensorFlow, Pandas etc). applications, with five high specification Nvidia cards.

In addition, UCL's Information Systems Division provides High Performance Computing facilities and a data-intensive computing facility. Over the REF period, our unit benefited from an exceptional growth in HPC facilities at UCL: share of *Legion, Grace* (in 2016 the largest and fastest HPC system in the UK University sector and ranked at 400 in the "Supercomputing Top 500" list of the fastest HPC systems in the world), *Myriad* for high throughput computing in data sciences (**Guillas** was on the UCL commissioning group). *Kathleen*, which entered service in January 2020, is a compute cluster designed for extensively parallel, multi-node batch-processing jobs, with high-bandwidth connections between individual nodes. It is named after Professor Dame Kathleen Lonsdale, a pioneering chemist and activist. UCL is also partner of several tier 2 HPC centres that provide a diversity of computing architectures, which are driven by science needs that are not met by the national facilities or universities. All these investments and partnerships resulted in significant benefits in research & impact (e.g. several papers and a KTP or multiple EPSRC IAA awards with industry support).

Finally, UCL was the first University in the UK to create a Research Software Development (RSD) group, whose goal is to help researchers to produce high quality research software, from the simplest scripts to complex simulations running on supercomputers. The group has supported a total of eight research and impact projects within UoA10 during the period, thanks to funding from EPSRC and Research England. The RSD group provides training in basic and advanced computing skills to staff, research and Master's students as well as contributing directly to research projects.

4. Collaboration and contribution to the research base, economy and society**4.1 Academic collaborations**

We have a huge number of research collaborations within and beyond the Mathematical Sciences, elsewhere in the UK and internationally, as evidenced by the large number of submitted outputs with co-authors based outside UCL (over 70% of those outputs with an author in the unit at the time of publication) and outside the UK (over 50%). This is partly driven by our many new recruits and their pre-UCL collaborations, but we also build new links as new opportunities arise.

Our staff travel extensively, to conferences or for research visits. Institutional support to develop new international research activities is provided by the Global Engagement Office in the form of travel awards of up to £2k (~£35k over the REF period); and longer visits are supported with sabbatical leave.

4.1a Collaborations within the Mathematical Sciences

We have an active series of international seminars (including the London-Paris Number Theory seminar (**Dokchitser / Petridis**, Heilbronn funding), the London-Paris Analysis seminar (**Parnowski**), and the Brussels-London Geometry seminar (**Schulze**, LMS funding)) which capitalise on our location close to St Pancras and bring international visitors to UCL. We also host visiting professors under various schemes (e.g., Mariel Saez-Trumper 2018-19 and Ovidiu Munteanu 2019 were both Leverhulme visiting professors organised by **Schulze**). Staff have held visiting professorships in France (**Cotar**, Paris-Nanterre, **Guillas** Paris-Saclay) and Japan (**Guillas**, University of Tokyo).

There are multiple strong individual links particularly with the US and North America, Singapore, Japan, India, Australia, Chile, and with many European countries. Royal Society International schemes (Exchanges Grants or Seminars) have been awarded to kick-start or strengthen these (**Cotar**, **Pokern**, **Guillas**) with Germany and India. Several staff hold or have held joint appointments with international institutions (**Sokal** with New York University, USA, **De Iorio** with Yale, USA, **Granville** with Montreal, Canada, **Barany** with the Hungarian Academy of Sciences, **Macrina** with University of Cape Town, South Africa and **Dellaportas** with Athens University of Economics and Business, Greece). At a less individual level, our Departments are present in several major multi-national consortia, including two 26-country COST networks (Accelerating Global science In Tsunami Hazard and Risk analysis, **Guillas**; Cosmology and Astrophysics Network for Theoretical Advances and Training Actions, **Boehmer**). Global Challenge Research Funding (GCRF from ESRC/NERC/AHRC and Research England) has facilitated international collaborations including the ESRC GCRF Resilient and Sustainable Interventions in Water-Energy-Food-Environment Mega-Systems 2017-21 (**Siddiqui**, Co-I).

We have strong coordinated links across London and the UK in some of our strongest areas of research, as evidenced by **Ni's** Programme Grant and interdisciplinary collaborations such as the many CORU projects run with London hospitals.

At the level of PhD training as described in Section 2.3, we collaborate with Imperial and King's College on the LSGNT, the only EPSRC/UKRI funded CDT in pure mathematics. We also lead the LTCC; and we are a member of the London Graduate School in Mathematical Finance.

Statistics manages the *Biometrika Trust* (**Isham** Chair of the Board of Trustees), which offers (since 2014) a two- or three-year research fellowship for early-career researchers in statistical theory or methodology. It is aimed at those among the most outstanding recent PhD graduates

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who are capable of self-direction and can be held in any research institution in the UK. The first recipients have held the fellowship at Cambridge, Glasgow and UCL Gatsby Unit (**Fernandez Aguilar**).

4.1b Interdisciplinary collaborations

Our interdisciplinary connections include joint academic appointments: one between Statistics and the Institute of Risk and Disaster Reduction (returned in UoA7); four between Statistics and NIHR UCLH/UCL Biomedical Research Centre (two returned in UoA2, two in UoA10); and one between Mathematics and the Institute of Women's Health (returned in UoA1). UCL's Met Office Academic Partnership (MOAP), started in April 2020, is another example of interdisciplinary connections: this partnership spans eight departments across three faculties, working collaboratively on transforming data sciences to secure the UK's world-leading position in weather forecasting and climate prediction. Mathematical scientists (**Betcke, Briol**) lead two of the four UCL-Met Office working groups as well as the overall MOAP (**Guillas**), which is supported institutionally by three PhD studentships and by a strategic research facilitator from the Office of the Vice-Provost (Research).

We also have, and strongly support, many ad hoc research collaborations beyond the mathematical sciences, notably with the Gatsby, Crick Institute, and UCL Engineering. We jointly supervise PhD students with other UCL departments as described in Section 2.3a: indeed, of the 159 research students graduating during the period, 73 had at least one supervisor from another unit. Similarly, our PhD projects with industrial partners (Section 2.3a) provide a clear pathway for collaboration between researchers and research users.

Finally, the unit provides training in mathematical and statistical methods to support research in other disciplines both within and beyond UCL. Examples include the annual *Practical Statistics for Medical Research* CPD training course provided by Statistics to medical researchers; and the annual five-week training in modern statistical methods and computing provided to each cohort of the London NERC Doctoral Training Partnership (typically around 25 research students from across the environmental sciences). These training activities promote awareness of the unit and its activities that can lead to fruitful collaborations, as well as promoting the uptake of modern mathematical sciences research methodology in other disciplines (e.g., the analysis underpinning large parts of the 2020 *State of Nature* report in the UK was done by ecologists working with **Chandler**, resulting from contact made during training activities).

4.2 Relationships with research users; impact

The unit undertakes a broad range of activities with non-academic research users. Our commitment to impact is evidenced by its inclusion in our recruitment criteria (see Section 2), and by our strategic expansion of impact-generating groups within the unit such as CORU (Section 1.1), where three new posts have been created in the period in recognition of the importance of their direct collaboration with clinicians and policy-makers in the healthcare domain.

More broadly, our impact strategy is facilitated by Enterprise Coordinators in both Mathematics and Statistics, with additional support from the Faculty Vice-Dean for Enterprise. UCL Innovation and Enterprise (UCL I&E) supports interactions with stakeholders and enterprises, for example:

- 26-28 June 2017, *Industrial Sandpit* (**Ovenden**, support from UCL research facilitators). Attended by 10 representatives from three external organisations: Dept of Transport, dstl, and Motorola Solutions and around 40 academics and postgraduates. The event led to the development of industry-focused research proposals, of which at least one (new collaboration between dstl and **Wilson**, with UCL Forensic Science) led to funded research beyond the REF period.

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- *8 November 2018, Networking meeting around applications of novel mathematical and statistical tools to security issues.* Organised by **Ovenden**. 60 participants, including representatives from five external bodies (dstl, DfT, Home Office, Office of Chief Scientific Advisor, Defence and Security Accelerator) and UCL participants from this UoA and beyond (Computer Science; Centre for Advanced Spatial Analysis; Clinical, Educational and Health Psychology; Geography; Civil and Mechanical Engineering; Security and Crime Science).

The period since REF2014 has seen a major uplift in the amount of funding available for impact-related work. The unit has made ample use of this, especially recently, including EPSRC Impact Acceleration Awards (14 across the departments, worth over £400K and with over 60% occurring since 2017); Knowledge Transfer Partnerships (3); UCL-industry funded impact PhD studentships for which UCL contributes 50% (10); EPSRC iCASE PhD studentships (4); and direct research and studentship funding from industry. UCL Consultants supports work carried out prior to or alongside research (£718,599 in total over the period). UCL Innovation and Enterprise supports and manages an increasing number of Knowledge Transfer Partnerships (KTPs), with awards in 2015 (**Guillas**), 2016 (**Silva**) and 2019 (**Fearn** and **Xue**). Impact also consists of dissemination of research to the commercial sector through invitations to speak in industry such as Twitter, Spotify, DeepMind (**Silva**), Barclays Investment Bank (**Marra**), or UBS, Bank of England, Bank of Japan, and Johannesburg Stock Exchange (**Macrina**).

Wilson has made active improvements to the impact landscape in the UK Mathematics community by her leadership of the IMA creation of the Hedy Lamarr Prize for Knowledge Exchange in the Mathematical Sciences (first award 2021). The long-term aim of the scheme is to improve the career recognition for KE in the Mathematical Sciences.

We support all staff to respond in an agile manner when research opportunities present themselves. Most recently, **Pagel** has been a key member of Independent SAGE since May 2020. Since June 2020 it has held weekly briefings in which she regularly presents the COVID-19 statistics and challenges (25-60k views each week across twitter livestream and YouTube). She also has had countless media appearances (BBC, Channel 4, Sky News etc. but also internationally with NBC, CNN, German, French & Swiss TV) on a weekly – and sometimes daily – frequency since July.

This work with Independent SAGE is an excellent example of UCL sharing our research with the wider public. In general, those engaged in outreach (**Wilson**, **Lotay**, **Olhede**, **Page**, **Pagel**, **Silva**) ensure that these activities are tied into their own research. **Lotay** ran workshops in collaboration with Lilah Fowler from UCL's Slade School of Fine Art, introducing schoolchildren to geometry in the fourth dimension. Another example is the work of **Olhede** and **Silva**, who have participated in public events related to their work with the UK Law Society policy commission on Algorithms in the Justice System established in 2018. The commission has taken evidence from a range of different experts on whether algorithms and their use within the justice system should be regulated, and if so, how such regulation could be formed.

4.3 Leadership in the Academic Community

Since REF2014, many new prizes and honours have been awarded. Highlights were given in Section 1.1a. Other awards have also been received for individual contributions. For example, **Northrop** received the Wiley-TIES Best Environmetrics Article Award in 2015 and **Baigent** received the Journal of Difference Equations and Applications Best Paper Award in 2016.

Elected fellowships and similar honours include **Fearn**, who was elected President of the International Council for Near Infrared Spectroscopy 2017-21; **Wilson**, President of the British

Unit-level environment template (REF5b)

Society of Rheology, 2015-2017; **Guillas** Vice-Chair of SIAM UQ 2015-17; **De Iorio**, Fellow of the International Society for Bayesian Analysis ISBA (2020) and **Manolopoulou**, elected 2019 to Board of Directors of ISBA. At the national level, **Baio** was appointed Scientific Advisor by the National Institute for Health and Care Excellence (NICE) and **Macrina** serves on the Scottish Financial Risk Academy Scientific Committee. **Isham** chaired the Scientific Steering Committee of the Isaac Newton Institute for the Mathematical Sciences throughout the current REF submission period.

Staff have been given many high-prestige keynote lectures during the period: in addition to the many examples listed in Section 1.1a, **Isham** was Bernoulli Lecturer at the 9th Bernoulli / IMS World Congress in 2016, and LMS-NZMS Forder Lecturer in 2018; **Wilson** gave the 2019 LMS Gresham Lecture; **Fearn** was keynote speaker at ANS2016 (Japan) and at the 2016 Chinese National NIR Conference in Wuhan; and **Zerbes** was invited speaker at the Heilbronn annual conference 2018.

4.3a Service on mathematical bodies

Our staff serve on **national Mathematics bodies** including:

EPSRC: Mathematical Sciences SAT (**Singer** 2017-2019), Peer Review college (**Betcke**, **Halburd**, **Vanden-Broeck**, **Vassiliev**, **Wilson**). Number Theory Landscape document (**Granville** 2015), Fellowship interview panels (**Wilson** 2017, **Halburd** 2019 (chair), **Zerbes** 2019), Prioritisation panels (**Vassiliev** 2014, **Zerbes** 2014, **Lotay** 2015, **McDonald** 2015, 2018, **Betcke** 2017, **Oksanen** 2019).

NERC: Peer review college Panel B core member (**Esler**, 2014-2020).

Isaac Newton Institute: Scientific Steering Committee (**Isham**, chair, 2014-2020); Scientific Advisory Panel, Newton Gateway (**Wilson**, 2019-20); Chair of correspondents and management committee (**Singer**, 2013-2015).

ICMS: Programme Committee (**Vassiliev**, 2015-2019), Nominating Committee (**Wilson**, 2019-).

London Mathematical Society: Council (**Singer**, 2012-2015, **Zerbes**, 2016-2018), Research Policy Committee (**Singer**, 2012-2018, **Zerbes**, 2019-), Prize Committee (**Zerbes**, 2020-), General Secretary (**McDonald**, 2020-).

Institute of Mathematics and its Applications: Vice-President (**Wilson**, 2018-2020), Research Committee (**Halburd**, 2015-; **Wilson**, 2013-).

Heilbronn Institute: Advisory Board (**Granville** 2015-2018, **Singer** 2018-).

A-Level Content Advisory Board Mathematics Panel and its successor: (**Wilson**, 2014-2018).

Royal Society: International Exchanges Committee (**Dokchitser**, 2016-; **Foscolo**, 2019-).

Our staff also serve **international Mathematics bodies**: both **Barany** and **Singer** have served on panels for *Deutsche Forschungsgemeinschaft* in 2020, and staff served as International experts on review panels for the Academy of Finland (**Smyshlyaev**, applied maths and statistics, 2014-15 and 2017-2019; **Petridis**, pure mathematics, 2017-18). **Baio** was Programme Chair of ISBA Section on Biostatistics and Pharmaceutical Statistics 2017-19; and **Hennig** Scientific Secretary of the International Federation of Classification Societies (IFCS) 2014-2018.

We do not list the many (well over 100) instances of conference and conference session organisation by staff members during the period. Three four or six-month Newton Institute programmes were organised by our staff during the period (**Parnovski / Sobolev** 2015; **Olhede** /

Unit-level environment template (REF5b)

Wolfe 2016; **Smith** 2017) along with three shorter programmes (**Isham** 2014, **Singer** 2015, **Guillas** 2018). A one-month programme at the Institute for Mathematical Sciences at the National University of Singapore was also organised by **Beskos** in 2018, and a Banff International Research Station workshop by **Oksanen** in 2016. **Granville** was co-organiser of the MSRI special semester on Analytic Number Theory (2017), and **Barany**, co-organiser of Oberwolfach recurring workshop on discrete geometry, 2014 and 2017. In addition, several of our staff co-organised ICMS workshops, including **E Johnson** (2016), **McDonald** (2017), and **Ovenden** (2020). Two major conferences ran at UCL: IUTAM Symposium on Wind Waves (**E Johnson**, 2018) and ICDEA (**Baigent**, 2019).

The Mathematics department publishes the journal *Mathematika* with **Sobolev** being the Managing Editor (previously **Smith**). The Department of Statistical Science publishes the journal *Biometrika*. In addition, staff hold (or held) the following senior editorial positions: **Barany**: Editor-in-chief, *Acta Mathematica Hungarica* (2016); **Chandler**: Joint Editor, *JRSSC* (2014); **Singer**: Editor, *Proceedings of the LMS* (2015-2018); chair, *AMS Mathematical Surveys and Monographs* (2015-2018); **Sokal**: Co-editor-in-chief, *Annales de l'Institut Henri Poincaré D* (2014-); and **Utley**: Editor-in-chief of *Operations Research for Health Care* (to 2016). Our wide range of standard editorial activity is listed below.

4.3b Editorial board memberships

These were held for the whole period unless specified.

Baigent: Journal of Difference Equations and Applications (2017-),

Baio: JRSSA (2016-), Significance,

Beskos: Statistics and Computing (2018-),

Bishop: Nature Scientific Reports,

Boehmer: Astrophysics and Space Science (2016-),

Burman: ESAIM: Mathematical Modelling and Numerical Analysis,

De Iorio: Bayesian Analysis (2019-), STAT,

Dellaportas: Bayesian Analysis (2018-), Biometrika (2012-19), Electronic journal of Statistics (2012-19),

Dokchitser: Royal Society Open Science (2017-).

Fearn: Journal of NIR Spectroscopy,

Granville: Bulletin of the American Mathematical Society; Mathematical Proceedings of the Cambridge Philosophical Society; Comptes rendus mathématiques de l'Académie des sciences du Canada; Annales des sciences mathématiques du Québec; Integers; Algebra and Number Theory; Mathematika; Electronic Journal of Combinatorics; Contributions to Discrete Mathematics; Online Journal of Analytic Combinatorics,

Griffin: Bayesian Analysis; Statistics and Computing; STAT (2012-2015), JRSSB (2013-2017),

Guillas: Computational Statistics & Data Analysis (2015-18), International Journal for Uncertainty Quantification (2019-),

Halburd: Journal of Difference Equations and Applications (2017-)

Hewett: IMA Journal of Applied Mathematics (2019-),

Manolopoulou: Bayesian Analysis (2019-),

Marra: Statistics and Computing (2015-), JRSSC (2018-), Dependence Modeling (2018-), Statistical Methods & Applications (2019-),

Northrop: Environmetrics,

Pagel: Operations Research for Health Care,

Sadeghi: Scandinavian Journal of Statistics (2019-),

Silva: Statistics and Computing (2013-19),

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Smith: J Eng Maths, Maths in Industry Case Studies,

Smyshlyaev: SIAM J on Mathematical Analysis,

Talbot: Bulletin / Journal / Transactions of the LMS,

Vassiliev: EMS Press (2015-),

Wilson: Proc Roy Soc A. (2018-), Journal of Engineering Mathematics, Journal of Non-Newtonian Fluid Mechanics,

Xue: Digital Signal Processing (2020-), Neurocomputing (2020-),

Zerbes: Mathematika (2018-).

Conclusion

The mathematical sciences are flourishing at UCL. This review period has seen a substantial expansion and diversification of activity, resulting from institutional investment combined with cultures of academic excellence, inclusivity and diversity. The momentum created during the period has set us well on the road to realising our vision for a UCL **Institute for Mathematical and Statistical Sciences (IMSS)**: we look forward to continually strengthening both our research portfolio, and our engagement with our peers and the wider community.