

<b>Institution: University of Bristol</b>
<b>Unit of Assessment: 10: Mathematical Sciences</b>
<b>1. Unit context and structure, research and impact strategy</b>

## Overview and highlights

1.1 The Unit of Assessment (UoA) is a world-leading centre for research that spans the breadth of modern mathematical sciences. Our vision is to engender impactful, cutting-edge research, delivered by outstanding and diverse staff, who are supported by an excellent environment. The following are some of the highlights during the assessment period:

- The renewal, development and growth of the partnership with the UK Government Communications Headquarters (GCHQ) through the Heilbronn Institute for Mathematical Research (HIMR) (see 1.5).
- The move to a building specifically designed for mathematical sciences. The extensively remodelled and refurbished Fry Building (£33M) co-located all UoA staff for the first time in over a decade and enabled expansion through associated recruitment to new permanent academic positions. Together these initiatives broaden our portfolio of research and evidence major investment by the University of Bristol (UoB) in mathematical sciences (see 1.6, 1.17, 3.5).
- The creation of new cohort training programmes for postgraduate research, including the Engineering and Physical Sciences Research Council (EPSRC) Centre for Doctoral Training (CDT) in Computational Statistics (COMPASS, 2019-, £11M<sup>1</sup>) and the Heilbronn Doctoral Partnership (HDP, 2020-), as well as academic involvement and leadership of CDTs hosted in other departments (Quantum Engineering, 2014-, Complexity Sciences, 2011-18, Future Communications, 2016-23). Taken together, these support at least 25 PhD students per annum (see 2.20-2.21)
- The embedding of knowledge transfer, its support and facilitation into the core of the UoA's strategy as evidenced by the initiatives in cybersecurity, national security and quantum computing; the breadth of our impact case studies and other engagement activities that span mathematical science; and the appointment of a UoA Knowledge Exchange (KE) Manager (2019-) (see 1.18-1.21).
- A strong commitment to equality and diversity, as evidenced by the award of Athena SWAN (Silver, 2018) and the adoption of unit-wide strategies to support an inclusive environment (see 2.25-2.30).
- The creation of new strategic partnerships in data science with the Jean Golding Institute, UoB (JGI) and the Alan Turing Institute (ATI), including theme leadership, and the establishment of a new EPSRC Prosperity Partnership with Google (£5.5M) and key leadership roles in the national Quantum Computing and Simulation Hub (£24M).
- Outstanding levels of research funding, featuring £33.2M reported in Ref4b, a 27% increase per annum from REF2014.

<sup>1</sup> Throughout we cite the full value of awards including partner and university contributions, aggregated across institutions.



**Figure 1: UoA highlights and the new catalyst for future work, the Fry Building.**

- The award of prizes (Fröhlich, Whitehead, Leverhulme and others, see 4.10), competitive fellowships (8 European Research Council (ERC) and 7 EPSRC) and election to Fellow of the Royal Society (FRS) (**Marklof**<sup>2</sup>).

1.2 These highlights testify to many changes within the UoA, including new directions in research, new partnerships, and a new physical environment. We are a large, research-focused UoA, based in the School of Mathematics (SoM), which sits within the Faculty of Science. At census date, the UoA includes 89 staff (85.9 FTEs); 62 are permanent research-and-teaching staff (21 Professors, 24 Associate Professors/Senior Lecturers, 17 Lecturers) and 27 are independent research fellows (2 Professors, 3 Senior Research Fellows, 22 Research Fellows), including 2 UoB Vice-Chancellor Fellows, which are prestigious 4-year awards. The submission includes 28 early career researchers (ECRs). The UoA additionally hosts 23 postdoctoral researchers (PDRs) and 67 PhD students. There has been recruitment to over 30 permanent positions during the assessment period; the UoA is now larger than at REF2014. In the run-up to the census date there was a higher turnover of senior staff than anticipated, but through an extensive recruitment programme, we have evolved and expanded our research programme, while sustaining our core strengths. (A detailed commentary on these changes is given in 1.7-1.16).

1.3 We are a research-intensive UoA, authoring over 1600 outputs during the assessment period. Our staff publish in leading international journals including Annals of Mathematics, Annals of Probability, Annals of Statistics, Communications in Mathematical Physics, Proceedings of the National Academy of Sciences and Nature. We collaborate internationally; every permanent

<sup>2</sup> Current academic staff at census date are written in bold, and those appointed within the assessment period with \*.



**Figure 2: Aggregated locations of the UoA's international co-authors (2014-19).**

member of staff has co-authored outputs with colleagues outside of the UK, including 46 of the top 50 institutions for mathematics (QS World University Rankings). Figure 2 depicts the locations of international co-authors and illustrates our global reach. UoA Staff are provided with modern digital and physical research infrastructure (see 3.5-3.10) and outstanding administrative and technical support, including expert advice from UoB's division for Research Enterprise and Development (RED) (see 3.11 and REF5a). Our commitment to work on societal challenges is demonstrated by the appointment of a UoA Research Impact and KE Manager (see 1.18iii). Together these facts evidence a dynamic and vibrant environment, which facilitates high-quality research outputs, success with applications for external funding and work that is impactful.

### Organisation and Context

1.4 Research activities of the UoA are coordinated through 5 research institutes: **Applied Mathematics; Mathematical Physics; Probability, Analysis & Dynamics (PAD); Pure Mathematics; and Statistical Science**. This themed structure, created in 2016, replaced the longstanding, traditional division into 'pure', 'applied' and 'statistics' groups to differentiate research leadership from teaching and departmental administration. The institutes deliver the strategic aims of promoting: deep intradisciplinarity, through thematically-coherent and agile research clusters; career development, particularly of ECRs; and broad interdisciplinary research, fostering outward-looking initiatives, a longstanding feature of the UoA (see 1.22-1.23). Importantly, research is not siloed; many staff have a secondary affiliation besides their primary institute. This flexibility catalyses interactions: approximately 5% of our submitted outputs are co-authored by staff from different institutes, such as between mathematical physicists (**Snaith**, Keating) and number theorists (**Booker**, **Conrey**). The Institute Directors (**Wiggins**; **Mezzadri**; **Dettmann & Toth**; **Walling**; **Johnson**) exercise leadership in research, together with the Head of School (**Robbins**), Directors of Research (**Liverpool**), Impact (**Dokchitser**) and Equality, Diversity and Inclusion (EDI) (**Ganesh**, Machin), Associate Chair of HIMR (**Burness**) and School Manager (Clark). They formulate and implement the research strategy (see 1.6) and steer the recruitment of staff and postgraduate students. Institutes convene high profile international meetings in Bristol. For example, PAD has organised a series of landmark conferences (PAD-2014,2018,2022) with over half of the speakers as International Congress of Mathematicians (ICM) lecturers, including Fields

## Unit-level environment statement (REF5b)

Medalists Hairer and Figalli. This event is now co-funded by the Clay Institute for Mathematics. Each institute has its own budget (combined value £63k per annum), which directors deploy to support these and other initiatives.

1.5 Our partnership with GCHQ through HIMR is arguably one of the largest and most successful programmes of KE in mathematics world-wide. Established in 2005 and renewed in 2014, HIMR is a key component in GCHQ's strategy for delivering national security. It provides a focused means for world-leading researchers to address operational issues of national security that are of utmost importance to the UK. HIMR has evolved into an internationally-renowned centre for mathematical research. UoB is its largest partner: the Chair (Keating, 2016-20; Grimmer, 2020-) and Associate Chair (**Burness**) are employed by UoB; the UoA hosts 22 of the 32 current Heilbronn Research Fellows (HRFs), including, since 2019, HIMR Data Science Fellows; and the UoA created and employs the Heilbronn Chairs in Arithmetic and Algebraic Geometry (**Dokchitser**), Probability (**Toth**), Data Science (**A. Lee\***, **Whiteley**) and Readership in Combinatorics (**Ellis\***). Additionally, the UoA employs three Senior Heilbronn Fellows (**Bober\***, **Crane**, **Patashnick\***), who split their time equally between independent research and HIMR and facilitate a sustainable pathway to impact.

## Review of REF2014

1.6 Our REF2014 submission reported the strategic aim to address both intra- and interdisciplinary challenges in mathematical sciences, motivated by the vision that many exciting and fundamental challenges lie between traditional boundaries in academic disciplines and sub-branches of mathematics. The new research institutes are part of our delivery of this aim (see 1.4). We further identified that new syntheses of mathematical approaches could address data-rich societal and academic challenges, underpinned by scientific computation. This strategic vision has been fulfilled as follows:

- We have recruited staff in Probability, Pure Mathematics and Statistical Science to tackle key problems in data science and cybersecurity, and existing staff have strategically broadened their research interests to address this challenge (see 1.7-1.16). This strengthens our partnerships with HIMR and ATI.
- New interdisciplinary research axes have been developed with Biology and Chemistry, supported through significant research council grants (see 1.14).
- Researchers in quantum computation have initiated a new partnership with Google, as well as being part of the leadership team for the National Hub in Quantum Computing and Simulation (see 1.13,1.23ii).
- Scientific computing has become embedded in the UoA's research activities, including computational number theory (**Booker**, Platt), computational statistics and data science (**Allison\***, **Andrieu**, **Fasiolo\***, **Gerber\***, **Kley\***, **Lawson\***, **A. Lee\***, **Liu\***, **Reeve\***, **Rubin-Delanchy\***, **Whiteley**, Wood), theoretical chemistry (**Wiggins**) and discrete element modelling (Russo, **Henkes\***)

Our research strategy was renewed in 2015 & 2019, driven by the move to the Fry Building and UoB investment in mathematics, to identify additionally the following priorities: growing new activity in geometry and topology, building capacity in probability, and strengthening existing activity in number theory and combinatorics. The implementation of our strategy and evidence of its success is described in 1.7-1.16.

## Unit-level environment statement (REF5b)

## Implementation of Research Strategy

1.7 The appointments of **Bober\***, **Klurman\*** and **M. Lee\***, coupled with HRFs (**Doris\***, **Fretwell\***, **Hughes\***, **Hsu\***, **Kopp\***) strengthen and sustain our activity in **number theory**. As a Senior Heilbronn Fellow, **Bober\*** (Washington)<sup>3</sup> provides key support to the HIMR partnership. **M. Lee\*** (Brown) was made a proleptic lecturer to secure her position after her Royal Society University Research Fellowship (URF) ends; she brings expertise in analytic number theory and automorphic forms, with links to dynamical systems. **Klurman\*** (MPIM, Bonn) is an international expert in multiplicative number theory. Some highlights from the group include: Wooley's transformative development of his efficient congruencing method (2014 International Congress of Mathematicians (ICM) invited lecture, 2017 Bourbaki exposé), which he and others have used to attack the Vinogradov Mean Value Theorem; **Dokchitser's** result on Selmer parity distribution for hyperelliptic curves underpinned a breakthrough by Bhargava (2014 Fields Medal) et al. on points of hyperelliptic curves in odd degree extensions; **Booker's** resolution of a 66-year-old question of Mordell, by finding representations of the numbers 33, 3 and 42 as sums of three cubes, attracted worldwide attention in the mathematics community and mainstream media.

1.8 Our ambition to nucleate research activity in **geometry** and **topology** was fulfilled through four outstanding appointments and coheres with strengths in geometric group theory, analysis and combinatorics. **Hagen\*** (Cambridge) brings expertise in hyperbolic geometry; his quasiflats theorem has settled open conjectures and provides a common framework for problems in hyperbolic geometry. **Erlandsson's\*** (Helsinki) appointment opens exciting directions at the interface between hyperbolic geometry and dynamics; her recent work unifies and extends results of Mirzakhani (2014 Fields Medal) on counting curves on hyperbolic surfaces. **Hassannezhad\*** (Mittag-Leffler) renews strength in geometric analysis following the retirement of van den Berg; she has solved long-standing problems including new bounds on eigenvalues of the Dirichlet-to-Neumann operator. **Babae\*** (Fribourg) brings expertise in algebraic and tropical geometry; a major achievement (with Huh) establishes that Demailly's sufficient condition for the Hodge conjecture (Clay Millennium Problem) is not necessary.

1.9 The appointments of **Ellis\*** (Queen Mary) as Heilbronn Reader in **Combinatorics** (replacing Wolf) along with **Tointon\*** (Cambridge) strengthen a key area of importance to the HIMR. **Ellis\*** opens up a new direction, extremal combinatorics, while **Tointon's\*** expertise in approximate group theory links combinatorics strongly to probability and geometry (see 1.8,1.10). Together with **Rudnev**, noted for influential work in geometric combinatorics on incidences between points and planes in three dimensions, and HRFs (**Grace\***, **Harper\***, **McInroy\***) they comprise a strong new and vibrant group.

1.10 Research activity in **probability** has been strategically strengthened by the appointments of internationally leading probabilists **Najnudel\*** (Cincinnati) and **Holroyd\*** (Microsoft, Rollo Davidson Prize Winner), joining a group (**Balazs**, **Crane**, **Ganesh**, **Johnson**, **Toth** & **Yu**) created during the previous REF period. Collectively, the group tackles problems in the fluctuation theory of interacting particle systems, random networks and stochastic processes on discrete structures, and builds intradisciplinary research through the interplay between probability, dynamics, number theory and quantum chaos (see 1.7,1.11,1.12). Major breakthroughs include **Holroyd's\*** striking resolutions of long-standing questions concerning phase transitions, cellular automata, and randomised algorithms, while **Toth**, invited lecturer at ICM 2018 and elected member of Academia

<sup>3</sup> The previous affiliations of new appointees to permanent positions are in brackets.

## Unit-level environment statement (REF5b)

Europaea (2016), has derived innovative results for random walks in irreversible random environments (see 1.11).

1.11 **Koivusalo\***'s (Vienna) appointment strengthens the UoA's group in **ergodic theory and dynamical systems** (**Dettmann, Jordan, Marklof**, Ulcigrai and HRFs **Dougall\***, **Allen\***), with expertise in quasicrystals and aperiodic order that builds upon the group's intradisciplinary research at the junctions of dynamical systems, number theory, mathematical physics, fractal geometry and probability (see 1.7, 1.12, 1.8, 1.10). Highlights from the group include **Marklof's** extension of his foundational work on the Boltzmann-Grad limit to a new class of transport equations for non-periodic scatterers exhibiting long-range order. Additionally, with **Toth**, he has given the first proof of a super-diffusive central limit theorem and invariance principle for the periodic Lorentz gas in three and more dimensions. International recognition of his contributions included an invited lecture at ICM 2014 and election as Fellow of the Royal Society (FRS).

1.12 Research in **random matrix theory** and **quantum chaos**, with connections to number theory, has strategically expanded to encompass many-body quantum systems and quantum gravity through the appointment of **Blake\*** (Massachusetts Institute of Technology (MIT)), who along with HRFs (**Jones\***, **Lees\***, **Piddock\***) and Vice Chancellor Fellow, **Maciazek\***, provide connections to the quantum information theory/computing (see 1.13) and through **Grava's** research on integrable systems and nonlinear pdes, which has catalysed new activity in fluid dynamics with **Eggers** (see 1.14). Evidence of the group's core strengths include **Mezzadri's** remarkable applications of random matrix theory and fundamental statistical analyses of many-body quantum systems, recognised through his award of the 2018 Frohlich prize. The group has also been strengthened by the appointments of **Bothner\*** (Kings College London), whose "truly brilliant" applications of the Riemann-Hilbert method to the analysis of special functions were cited in his 2019 Gábor Szegő prize, and by **Najnudel\***, who obtained the most precise estimates to date of extreme values of the Riemann zeta function and characteristic polynomials of unitary matrices, a breakthrough in an intensely active area initiated by Keating.

1.13 Under the direction of **Linden** and strengthened by the appointment of **Montanaro\*** (Bristol), the **quantum information theory/computing** group exercises research leadership within UoB, nationally and across the discipline (see 1.23ii), including directorship of the Bristol Quantum Information Institute (**Linden**), which is one of seven specialist research institutes in UoB, with oversight of theoretical and experimental advances, training and commercialisation. **Linden** and **Montanaro\*** received a £5.5M Prosperity Partnership grant with Google (2019); at the time, this was Google's only academic partnership outside the USA. **Montanaro\*** made essential contributions to the mathematical theory underpinning Google's breakthrough work on quantum computational supremacy, whose announcement made international headlines. He was also invited to write a highly influential Nature review on these developments. **Montanaro's** achievements have been recognized by fellowships from EPSRC and ERC, and a Whitehead prize for "outstanding and strikingly diverse contributions across the field of quantum computation and quantum information theory".

1.14 Continuum mechanics, dynamical systems theory and statistical physics provide the overarching themes that link research in applied mathematics and underpin vibrant collaborations with groups from other disciplines (see 1.22-1.23). During the assessment period new activity has been strategically grown in **chemical physics**, **biological materials**, and **soft matter**, while maintaining excellence in **fluid dynamics** and **material science**. For example, **Eggers'** pioneering investigations of singularities in fluid and solid mechanics, cited in his 2017 Stanley Corrsin Award, have recently elucidated the near-conical tips of strongly deformed fluid interfaces; **Slastikov** has

## Unit-level environment statement (REF5b)

resolved long-standing problems in the structure of defects in the Landau-de Gennes and Ginzburg-Landau models; and state-of-the-art numerical simulations by Russo (Royal Society URF, ERC Starting Grant, Leverhulme Prize) have led to the discovery of new structures and phases in water and glasses. Turning to new activities, as Principal Investigator (PI) of the largest programme grant awarded by EPSRC's Mathematics Panel (£5M), **Wiggins** leads an international collaboration applying methods of dynamical systems, semiclassical quantum mechanics and machine learning in a phase-space setting to advance the state-of-the-art treatment of chemical reaction dynamics. Alongside this growth, the strategic appointments of **Henkes\*** (Aberdeen) and Vice-Chancellor Fellow, **Bennett\***, two outstanding researchers at the interface of soft matter, continuum mechanics, fluids and cellular processes, strengthen activity in biological materials and applications. They join **Liverpool**, an internationally-leading authority in active matter, who directs the modelling theme of BrisSynBio, an EPSRC/Biotechnology and Biological Sciences Research Council (BBSRC)-funded, UoB multidisciplinary research centre (£14M). A key recent result (with **Linden**) is a novel theoretical framework for the rational design and self-assembly of programmable, man-made peptide cages and sheets.

1.15 Driven by the UoA's strategic ambition in Data Science and Cybersecurity (see 1.6) and matched by an extensive programme of appointments (9 Lecturers and 4 Professors during the assessment period), research activity in **statistical science** has grown in size and scope. There is synergy with HIMR, underlined by the creation of two new Heilbronn Chairs in Data Science (**A Lee\*** (Warwick) and **Whiteley**); the appointment of **Allison\*** (GCHQ), former Director of HIMR with expertise in cybersecurity; the secondment of **Rubin-Delanchy\*** (Oxford) to HIMR as Data Science Lead; recruitment of 2 HIMR Data Science Fellows (**Doris\***, **Tickle\***); and the creation of an international HIMR Data Science visitor programme (see 4.5). A new exchange programme with Institute of Statistical Mathematics (ISM), Japan (2019-) and a new Data Science seminar with JGI also invigorate the research programme.

1.16 The expertise of new staff broaden the research portfolio to include: statistical machine learning (**Liu\*** (ISM), **Reeve\*** (Birmingham)), anomaly detection and cybersecurity (**Rubin-Delanchy\***), energy forecasting (**Fasiolo\*** (Bristol), see 2.17,4.6), information theory (**Jaggi\*** (Chinese University Hong Kong)) and collaborations with the UoB Medical School (**Lawson\*** (Bristol), Wellcome Trust (WT) Sir Henry Dale Research Fellowship (SHD), see 1.230,4.6). During the assessment period, **Andrieu, Gerber\*** (Harvard), **A. Lee\*** and **Whiteley** produced ground-breaking contributions to the theory and methodology of Monte Carlo algorithms, notably leading to **Gerber\***'s paper on Sequential quasi-Monte Carlo being a read paper at the Royal Statistical Society (RSS) and involvement in EPSRC grants (iLike, £2.4M, CoSinES, £3M and Bayes-4-Health, £3M). Staff have held EPSRC fellowships (Nason, Wood), Turing Fellowships (**Andrieu, Cho, A. Lee\***, **Liu\***, Nason, **Rubin-Delanchy\***, **Whiteley**, Y.Yu), leadership positions with ATI (**A Lee\***, Programme lead for 'Statistics at Scale') and RSS (Nason, **Andrieu, Cho**), and Rougier was seconded to the Cabinet Office (see 1.19). The institute hosts the COMPASS CDT (see 2.20) and has built external partnerships with companies such as Atomic Weapons Establishment (AWE), EDF Energy, IBM, Improbable, Office for National Statistics (ONS) & Sparx.

## Future Plans

1.17 As befitting a large UoA with substantial research activities in a broad range of mathematical sciences, we have ambitious plans to expand into new areas and cross-fertilize new intra- and inter-disciplinary collaborations. These plans are supported by UoB's ongoing commitment to sustain and enhance our international standing, strengthened by our existing and emerging strategic partnerships, and enabled by our successful track record of nurturing new

## Unit-level environment statement (REF5b)

activity into internationally leading research groups – examples from our past include quantum information, ergodic theory and probability.

- In analysis, we plan new activity in the calculus of variations and nonlinear PDEs to connect with existing research in Applied Mathematics and Mathematical Physics.
- With applications to climate science, soft matter, biological and chemical systems, we plan to grow scientific computation and thus enhance collaborations with earth, geographical and biological sciences, physics and chemistry.
- Motivated by wide-ranging applications and societal challenges in health, physical and social sciences, we will continue to expand activity in data science, machine learning and artificial intelligence.
- We plan to build further new capacity to supplement and sustain core strengths in: (i) number theory, algebraic geometry and topology; and (ii) quantum computing, allied with UoB's Quantum Technology Innovation Centre and our strategic partners (see 1.18i, 1.23ii, REF5a).

## Impact Strategy

1.18 The UoA's ambition of engaging with end-users of research in industrial, commercial and policy-making settings is embedded within our research culture. Enabling strategies include the following:

- i. Strategic Partnerships: HIMR is the conduit of our major strategic partnership with GCHQ (see 1.5) and is widely viewed as an exemplar for collaborations between mathematicians engaged in fundamental research and end-users of research ('The Era of Mathematics', EPSRC Review of KE in Mathematical Sciences, Bond 2018). The UoA also initiated partnerships in quantum computing including Google (see 1.13). Additionally, the UoA launched an Industrial Advisory Board (lead: **Allison\***) to coordinate and catalyse new activities.
- ii. Impact Study Leave: we introduced an innovative study leave scheme (2014) to provide administrative and teaching buy-out for staff members to initiate or sustain impact and KE activities. For example, this scheme enabled Rougier to introduce modern statistical methods to National Risk Register (Cabinet Office, UK) and **Hogg** to deliver training in mathematical modelling of volcanic debris flow hazards to national geophysics agencies in Colombia, Ecuador, Peru, and the Philippines.
- iii. Institutional & UoA Impact Support: We are cognisant of the barriers faced by mathematics, identified by the Bond Report, and of the necessity to embed KE translators within the UoA. Therefore, we created the role of UoA KE Manager (2019-) to facilitate staff engagement with end-users of research, coordinate industrial outreach, and generate postgraduate placements. The UoA Director of Impact (**Dokchitser**) has overall responsibility for the development of impact-related work, including assisting with securing funding and highlighting impact opportunities, particularly for ECRs; he reports to every School Assembly. The UoA Director of Public Engagement (**Erlandsson\***) coordinates and facilitates external engagement activities (see 4.7); this role was created in 2014 to deliver our vision for communicating research to a general audience. Together, these three UoA positions supplement UoB's extensive support for impact and commercialisation (see 3.11, REF5a), which includes coordinating funding streams for impact-related work, such as the EPSRC Impact Acceleration Account (IAA, see 2.17, 3.3).

## Unit-level environment statement (REF5b)

1.19 These initiatives have supported a broad range of engagement and impact in many sectors, including national security, energy, meteorology, banking, manufacturing, wireless networks, epidemiology, natural hazards, the environment, and climate change. We have a strong focus on influencing policymaking and have advised major decision bodies in and outside the UK, including the Cabinet Office, Police, Home Office, Office for National Statistics, United Nations, International Geophysics Agencies and Volcanic Ash Advisory Centres. Our REF2021 submission includes seven impact case studies that span the breadth of mathematical science, although our engagement extends beyond these (see 2.17-2.18,4.1-4.7). Some case studies are classified, arising through our strategic relationship with GCHQ, and the UoA's support of the HRFs (see 1.5). Others are associated with our support of statistical science, and of interdisciplinary work. These are additionally enabled by the UoB University Research Institutes (URIs) in environmental, data and health sciences (Cabot, Jean Golding and Elizabeth Blackwell Institutes, respectively), which provide a sustainable pathway to impact (see REF5a).

## COVID-19 Response

1.20 There has been considerable research within the UoA in response to the COVID-19 pandemic, illustrating the dexterity of UoA researchers to respond to emergent societal challenges, to engage with and impact national policy makers, and to communicate results to the public. Early in the pandemic when data were sparse, **Fasiolo\***, **Green** and Wood drew attention to biases in models due to inadequate data (Lancet, May 2020) and called for an appropriately designed random testing campaign. **Lawson\*** provided the underpinning statistical methodology for regional NHS contingency planning (BMJ, June 2020). As part of the Royal Society's DELVE Action Team tasked to provide mathematical, data-driven advice to decision makers, **Ellis\*** co-authored two reports submitted to SAGE, one of which was cited directly by the UK Chief Medical Officer to explain government policy on opening schools. In April and June 2020 at the request of the Department for Health and Social Care, **Crane** co-organised (and 9 UoA staff contributed to) national study groups that wrote working papers analysing consequences of post-lockdown activities, while **Johnson's** analysis of the pandemic in terms of non-standard measures of population density led an invitation to the Parliamentary and Scientific Committee (June 2020). Finally, **Lawson\*** and **Johnson** have regularly contributed to media coverage of the pandemic, featured in the Guardian, New York Times, BBC and the Spectator.

## Future Impact Strategy

1.21 Motivated by the belief that mathematical science has a central role in scientific, technological and societal challenges, we identify the following mechanisms to deliver and support impact and engagement, and will:

- i. Provide staff with outstanding UoA assistance to plan for and exploit opportunities to engage widely, through the roles of Directors of Impact and Public Engagement, and KE Manager, who champion impact and provide integrated support with UoB business development team (REF5a). Researchers will continue to be supported by these UoA officers to access IAA funding (see 2.17,2.18,3.3),
- ii. Use the UoA Industrial Advisory Board to create conduits for impact through collaborations, secondments and career opportunities for postgraduate research students (PGRs).
- iii. Build new external partnerships leveraged through the COMPASS CDT and initiatives in quantum technologies, focussed through the new UoB campus, Temple Quarter Enterprise Campus (TQEC) (see REF5a). **Linden** chairs the steering group of the Quantum

## Unit-level environment statement (REF5b)

Technology Innovation Centre, which has received £35M from the West of England Combined Authority and will move to TQEC on its completion.

- iv. Ensure that impact activities are counted in the staff workload model. This is the successor to our impact study-leave scheme. Impact and engagement activities are also part of the assessment of promotion and progression within UoB's procedures (see 2.10,2.13).
- v. Train the next generation of researchers through curricula that engage with industry. Planned activities include the CDT in Statistical Science (COMPASS, lead: **Whiteley**) and HDP in Discrete Mathematics (lead: **Burness**) (see 1.16,2.20-2.21).

## Interdisciplinary activities

1.22 Underpinned by the conviction that exciting and challenging mathematics arises from the interplay with other disciplines, the UoA values interdisciplinary research highly and has a long-established track record of its support. This research is in part enabled by the URIs, together with the Specialist Research Institutes (SRIs), which operate across faculty boundaries to facilitate interdisciplinary research through focused projects, workshops, and pump-priming funds (REF5a). During the assessment period we made several strategic appointments of staff with an interdisciplinary research profile (e.g. **Henkes\* & Bennett\***, mathematical biology; **Lawson\***, medical statistics), contributed to multidisciplinary CDTs (see 2.20) and used our EPSRC Doctoral Training Partnership to support PGRs between traditional disciplines. Our workload model takes explicit account of co-developed activities with other disciplines (see 2.13) and through strategic academic recruitment (see 1.17) and continued unit and institutional support, we plan that interdisciplinarity will remain central to our vision.

1.23 The following examples illustrate the breadth of interdisciplinary activities:

- i. **Hogg's** work with volcanologists in Earth Sciences, UoB (Natural Environment Research Council (NERC) consortium, VANAHEIM, £2.7M), on volcanic ash plumes produced highly cited work that enables the quantification of the volcanic source strength from observations of the height of the plume rise through the atmosphere. This calculation is used operationally to assess the risk posed by an eruption to aircraft flights – and is reported as one of our case studies. It formed part of the submission that earned the Volcanology Group a Queen's Anniversary Prize (2015). His ongoing collaborations strengthen resilience to volcanic hazards (NERC Consortium, Strengthening Resilience in Volcanic Areas (STREVA), £2.7M) and co-developed a lahar-hazard assessment tool that is used internationally, including the Philippines (Newton SE Asia Fund, £400K).
- ii. **Montanaro\*** and **Linden** collaborate widely with quantum information research scientists and lead national and international activity. In addition to roles reported in 1.13 and 1.21iii, **Linden** is on the Management Committee of the National Quantum Computing and Simulation Hub (£24M), in which both **Linden** and **Montanaro\*** have been work-package leaders. **Montanaro\*** gave evidence on quantum technologies to the House of Commons Science and Technology Select Committee, whose report advocated an increased focus on software development for quantum computers as well as hardware. **Linden** and **Montanaro\*** were two of ten authors of the European Quantum Software Manifesto. **Montanaro\*** is co-founder of the quantum software startup, PhaseCraft, which secured £750k in pre-seed investment (see 3.11).

## Unit-level environment statement (REF5b)

- iii. **Lawson\*** provides strategic links with the Integrative Epidemiology Unit (IEU), School of Medicine. His research has driven a shift in the IEU away from using simplistic statistical methods and further KE is facilitated through an EU RISE award (EUR2M). Amongst many high-profile outputs, he co-led a Nature article on the population genomics of the Viking world, which generated media attention including an upcoming TV documentary. **Lawson\*** is on the JGI Steering Committee and works with the Elizabeth Blackwell Institute and local NHS.

### Open Research Environment

1.24 The UoA is aligned with UoB's open research strategy: all accepted papers are posted on the University's publication repository (PURE). When necessary, UoB directly funds charges levied by publishers to ensure open access for research outputs; the UoA has received over £100K during the REF period to this end. The UoB's dedicated Research Data Storage Facility provides a long-term repository for all research data. Additionally, many papers are deposited on preprint servers (usually arXiv) after submission and often before acceptance. Where computational code is a key deliverable from research, the standard practice is to preserve and release the commented and documented code under an open license using a code repository platform (e.g. **Cho, Doris\***, **Fasiolo\***, **Henkes\*** and **Wiggins** use GitHub, amongst many others). PIs budget in grants for development and maintenance of webpages to share results with the wider scientific community, and large projects and CDTs employ KE specialists.

### Research Ethics

1.25 All UoA PIs work with UoB professional services (and the Research Ethics Officer, in particular) in the planning and implementation phases to ensure that their programmes meet relevant ethical and legal standards and are approved by the Faculty Research Ethics Committee. For example, **Hogg's** work on the resilience of communities in Peru to flash floods, supported by Global Challenges Research Fund, underwent this approval process. Recognising that training in ethics and responsible innovation is vital for all researchers, the UoA has introduced postgraduate courses, which are part of the formal training delivered by the CDTs but available to all.

## 2. People

2.1 Staffing is the most vital element of our research strategy and our aim is to recruit and nurture outstanding talent. All 62 teaching and research staff and 5 research fellows hold permanent contracts; the other submitted fellows (19 HRFs; 1 Marie Curie and 2 Vice Chancellor Fellows) have fixed-term contracts. Five permanent staff are employed on a part time basis. We have recruited over 115 PDRs during the assessment period. PhD student numbers have also increased from 61 (REF2014) to 67. We host two cohort-based doctoral training programmes (COMPASS and HDP), which together will admit at least 15 students per year, leading to further growth of postgraduate researchers (PGRs).

### Recruitment

2.2 Recruitment at all career levels is of utmost importance and candidates are drawn from international pools. Just over half of our appointments to permanent positions during the assessment period were from overseas institutions, including Chinese University of Hong Kong, Harvard, MIT and University of Tokyo (see 1.7-1.16). Although we recruit permanent academic staff strategically, a candidate's research quality is the key factor in their

## Unit-level environment statement (REF5b)

appointment. Hiring follows a rigorous process, with international experts engaged as independent assessors for senior appointments (Associate Professor and Professor). Evidence of the quality of our junior appointments to lectureships is that many are promoted rapidly; 4 lecturers appointed during the assessment period were promoted to Associate Professor, 2 of whom (**A. Lee\***, **Montanaro\***) are now Professors.

2.3 EDI considerations are central to every stage of the recruitment process. Following our Athena SWAN Silver Action Plan, we have adopted the following strategies: (i) explicitly inclusive language in job advertisements, which are reviewed by the UoA EDI Co-Directors; (ii) separate shortlists for male and female candidates, which are combined for the interview stage; (iii) diversity in appointments panels, with the aim to achieve gender balance; (iv) obligatory unconscious bias training for panel members. These initiatives have resulted in a 50% significant increase in BAME staff relative to REF2014 and an increasingly gender-balanced staff profile. For lectureships (the majority of our advertised positions), offer rates are similar between male and female candidates.

### Early Career and Newly-appointed Staff

2.4 The UoA is pleased to host 28 ECRs. They, and other newly appointed permanent staff, are given reduced administrative responsibilities and those with teaching duties, reduced loads (typically a single unit, 36 hours, per year). They, and all staff, are assigned an academic mentor and join at least one of the research institutes. New lecturing staff receive a start-up grant (typically £6K) and are encouraged to take advantage of emergent research opportunities, such as applying for prestigious fellowships (see 3.2). ECRs rapidly build important collaborations within the UoA. Recent examples include **Blake\*** and **Linden's** work on models of scrambling of quantum information (Physical Review Letters), and **Gerber\*** and **Whiteley's** work on resampling (Annals of Statistics). Furthermore, ECRs often lead our Distinguished Visitors programmes and convene workshops, all financially supported by the UoA. Examples include high energy physics (**Blake\***, COVID-postponed until 2021), Toric arrangements (**Babaee\***) and Spectral Analysis of time series (**Kley\***, **Cho**, Nason).

2.5 The UoA has long-standing excellence in recruiting and nurturing the career development of outstanding ECRs, who go on to make discoveries that command attention from the international mathematics community. One consequence of this strategy has been that the latter half of the assessment period (2017-19) witnessed an unprecedented turnover of staff, including the departure of 9 professorial staff. Of the departures, 6 of these 9 professors, including two FRS, joined the School at an early stage of their careers and have moved to prestigious positions including the Sedleian Chair at Oxford (Keating), GI Taylor Chair at Cambridge (Kerswell), and senior professorships at Imperial College (Nason), IST Austria (Browning) and University of Zurich (Gorodnik and Ulcigrai).

### Research Fellows

2.6 Research fellows and PDRs add very significantly to the UoA's vitality. They provide outstanding role models for our large cohort of PGRs; they lead reading groups, seminar series, deliver graduate courses and champion public engagement activities (see 4.7). We hold an annual appointment of HRFs, who under an innovative employment model divide their time between their own research programme and classified research led by GCHQ (see 1.5). These positions are highly sought after, with approximately 20 applications for each position. To tackle the under-representation of women, UoA staff are rewarded with research funds for

## Unit-level environment statement (REF5b)

encouraging female applicants. HRFs have access to HIMR visitor funds and have organised over 10 international workshops in Bristol since 2016, featuring Cole Prize winners Guralnick and Maynard, and EMS Prize winner Adiprasito.

### Professional Development

2.7 All staff access CREATE, UoB's scheme for continued professional development for academics (REF5a). Several have completed training in Staff Reviewing, Recruitment and Being Inclusive and UoB's Leadership Programme; these sustain succession within the UoA leadership. Focused training to support applications for funding is regularly delivered by RED. To support diversity, the UoA prioritises the participation of staff with protected characteristics at over-subscribed courses. Additionally, ECRs receive formal training in undergraduate teaching (see REF5a), and the UoA provides additional support through a dedicated Teaching Mentor and peer observations.

2.8 UoB is a signatory to the Concordat to Support the Career Development of Researchers and has a comprehensive institutional strategy, embodied within Bristol Clear, to support researchers and enable their career development (REF5a). HIMR also runs a national professional development programme (lead: **Burness**), and the UoA offers bespoke training tailored for mathematical researchers. This includes mentored teaching experiences, regular panel discussions and presentations, some delivered by external speakers on topics key to future career success, such as "Shaping a research programme" and "How to apply for a job", and mock interviews. Evidence of the value of these initiatives is that 29% of the PDRs moved directly to permanent lectureships (or equivalent) at institutions in UK, USA, Canada and Israel. Other destinations include further postdoctoral research in academia or industry (66%) and teaching (4%).

### Grant-writing support

2.9 To support and provide strategic advice, all UoA staff proposals are reviewed by the UoA's Research Committee, with input from the Director of Impact. Larger grants, fellowships, first grants, programme grants and initiatives such as CDTs are additionally supported by RED, including practice interviews and coaching from external consultants. Staff with unsuccessful grant applications meet with the Director of Research to review feedback and identify future opportunities. This system of support is effective. For example, all 7 ECR applicants succeeded with their First/New Investigator Grants during the REF period.

### Promotion, Progression and Staff Reviews

2.10 The UoA holds mentoring and service reviews for ECRs and operates an annual Staff Review system for all staff, which involve meeting with a senior colleague. Emergent concerns are reviewed by the Head of School and addressed as appropriate; examples include rebalancing workloads to create more research time, provision of study leave and assigning leadership roles to enable career development. Following the UoB career structure, newly appointed lecturers progress steadily towards senior lecturer and all 18 eligible UoA staff have achieved this progression during the assessment period without impediment. Additionally, staff may be promoted to Associate Professorial and Professorial grades. All eligible staff may enter this annual process and Institute Directors play an active role in advising junior staff. Each submitted case is assessed by UoB promotion committees, who seek external reviews and assess accomplishments in research, teaching, administration and wider contributions to the subject, including engagement with end-users of research. The UoA has had several promotions during the assessment period,

## Unit-level environment statement (REF5b)

including to professor (**Booker**, Collins, **Grava**, **Hogg**, **Johnson**, **Mezzadri**, **Montanaro\***, **Robbins**, Rougier, Ulcigrai) and to Associate Professor (**Balazs**, **Booker**, **Burness**, **A.Lee\***, Leslie, **Mackay**, **Montanaro\***, Mohammadi, Russo, **Whiteley**, **Wiesner**). Staff with unsuccessful promotion cases receive feedback from the Dean and Head of School.

### Leadership and succession

2.11 Senior staff provide leadership in research within UoB, UK and internationally (see 4.8). UoA senior roles with a research-related remit include the Head of School; Directors of Research Institutes, Research, Impact, Postgraduate Studies, & EDI; and Associate Chair of HIMR. UoA members have served at an Institutional level, including Dean (**Marklof**, 2018-) and Graduate Dean of the Science Faculty (**Robbins**, 2013-2017, **Dettmann**, 2017-), **Linden's** leadership of the Quantum Information Institute and **Burness's** leadership role with HIMR. Given the high proportion of ECRs, we are aware of the vital importance of research leadership and mentoring, tasks that are recognised through the workload model (see 2.13-2.15). We plan for succession in leadership roles by seeking expressions of interest from UoA staff 6-12 months in advance of the end of a term, particularly encouraging those with protected characteristics to increase diversity in the roles (see 2.26). Leadership training is promoted, and the UoA ethos of collective responsibility and good citizenship have ensured smooth transitions.

### Emeritus staff

2.12 The UoA is keenly aware of the valuable contribution from staff who have reduced their full-time positions (e.g. **Green**, McNamara, Van den Berg) and provides support through part-time salaries, office space and administrative assistance. We capitalise on their expertise through mentoring junior staff and contributing to postgraduate supervision. Launched in 2016, **Green** leads the UoA Statistics Clinic that provides highly-valued, free consulting for approximately 150 UoB researchers per year.

### Workload model

2.13 The UoA introduced a new workload model in 2015 to provide a fair and transparent mechanism for allocating teaching and administrative responsibilities and ensuring an appropriate balance between these duties and research. The aim for staff with research and teaching duties is a division of time commitment of 40% research, 40% teaching and 20% administration and leadership, while for 'research-only' staff, the aim is at least 80% commitment for research. This guide is applied to both full- and part-time staff, as well as those on fixed contracts. The UoA workload model has specific allowances for research-related activities including grant applications and management, engagement with end-users of research (including initial development through to writing-up impact case studies), mentoring postdocs, supervising PGRs and periods of secondments (see 2.17).

2.14 The workload model facilitates a sabbatical scheme, whereby staff re-balance their duties to facilitate research leave. The UoA has restructured its undergraduate teaching and personal tutoring so that most staff can concentrate their responsibilities into a single semester if they choose, allowing them to focus on research for the remainder of the year, as well as to travel (e.g. several staff have participated in international residential research programmes, see 3.12,4.12). During the assessment period, all requests for research leave have been granted.

2.15 Due to current gender imbalance in the discipline and the aim of ensuring gender balance, UoA female staff typically are asked to join working groups, committees and panels more

## Unit-level environment statement (REF5b)

frequently than male staff. Therefore, in recognition of these duties, all female staff are given extra allowance in their workload allocation (which is equivalent to a semester's delivery to a tutorial group). Where a committee's terms of reference would result in male-dominated membership, female staff are co-opted in an 'attend and contribute but no-work' capacity.

### Knowledge exchange

2.16 The UoA enthusiastically encourages and supports staff interactions with business, industry and the public, recognising the enrichment to our research portfolio brought by mathematical challenges from these arenas. We facilitate: secondments, which may be funded directly by the associated company/agency or through EPSRC IAA (see 2.17); industrially funded grants; spin-out companies; knowledge exchange fellowships; collaborative agreements; and consultancy work. The UoA also uses its own resources to support knowledge exchange that cannot be funded from other streams.

2.17 HRFs have collaboration with GCHQ on issues of national security built into their employment contracts (see 2.6). The UoA has strategically supported other secondments to HIMR, including: **Booker** (2016-18) to bring expertise in computational number theory; **Rubin-Delanchy\*** (40%) to lead the Data Science team; and **Allison\*** is employed part-time by GCHQ (50%). Examples of outward secondments funded by EPSRC IAA include partnerships with JBA Trust, to introduce topographic uncertainty to flood models (**Hogg**, Rougier), and NASA, to transfer advances in rateless codes and energy efficiency to space communications (**Dettmann**), the latter arising from an EPSRC-funded project (£1M) with Toshiba that featured other inward and outward secondments. Examples of industrially funded placements include **Rubin-Delanchy\***'s work with Wessex Water on leak detection and Wood and **Fasiolo\***'s work with EDF Energy (France) on the development of regression modelling tools focused for operational forecasting of grid load in France and elsewhere (see 4.6).

2.18 UoA staff have received funding from Innovate UK. **Porter** was a co-investigator in a consortium including marine renewable specialists Mojo Maritime, Catapult ORE and DNV-GL to determine the potential for a Wave Energy Converter fitted with Witt Energy Ltd's novel energy conversion mechanism. **Porter**'s expertise in the mathematical theory of energy extraction from ocean waves enabled the assessment of the feasibility of their prototype for ocean deployment. **Montanaro\*** collaborated in an Innovate-funded project with British Telecom, investigating applications of quantum algorithms in the telecommunications industry (2017). The UoA also supported **Montanaro\***'s time in co-founding of Phasecraft (see 1.23ii). Finally, through an IAA, **Linden** is funded to build commercial collaborations in quantum technologies.

### Research Students

2.19 During the REF period, the UoA admitted 131 PGRs. Competition for places is strong with over 8 applicants for every place. Approximately 50% of applications were from outside the European Union. Several applicants won prestigious international studentships from UoB, Marshall, EPSRC International and Chinese Scholarship Council. Recruitment of PGRs is driven by the UoA's research reputation, online advertisements, and recruitment events, including an annual two-day meeting 'Women in Mathematics', instigated and funded by the UoA, for female and non-binary final-year mathematics students. The event encourages potential students to continue to PhD studies and features presentations from mathematicians in academia and industry. Female and non-binary applicants account for 27% of PGR applications and have received 27% of offers.

## Unit-level environment statement (REF5b)

### PGR Funding

2.20 PGR funding is strategically deployed to support research priorities. Traditionally under-represented groups take priority for funded places upon equal qualification. Over 50% of current PGRs are funded by UoB's EPSRC Doctoral Training Partnership (DTP). The UoA also co-funded with HIMR 1-3 studentships per year for female or non-binary postgraduates and strategically allocated DTP funds with the aim of reducing historical imbalances in the discipline (2016-19). Six current PGRs are partly funded by industry partnerships (e.g. GCHQ, National Flood Insurance Programme) and 4 study part-time. Since 2019, we have run the COMPASS CDT, which provides cohort-based training in computational statistics and data science for 10+ PGRs per year. The UoA played a leading role in setting up 3 EPSRC-funded CDTs - Quantum Engineering (**Linden** chairs the steering committee), Future Communication, and Complexity Science, as well as the 4-year PhD programme in Neural Dynamics funded by the Wellcome Trust. Several of the UoA's PGRs are co-supervised with colleagues in Science and Engineering, and current links with industrial partners include Liverpool Victoria, GCHQ, GlaxoSmithKline, Wessex Water, Shell, Office for National Statistics & Atomic Weapons Establishment. An increasing number of studentships are funded as CASE awards (e.g. 2 with IBM in 2020).

2.21 In response to the identified lack of opportunities for doctoral training in pure mathematics, the UoA and HIMR established the HDP (2020-) in partnership with mathematics departments at Oxford and Manchester. This endeavour initially funds 8 PGRs per year to provide high-level training in discrete mathematics and other areas of importance to HIMR, along with placements to work on HIMR's internal research programme, thus participating directly in projects that impact national security.

### PGR Training, monitoring and support

2.22 In addition to specialist training, PGRs have individual training programmes involving over 100 hours of assessed courses to maintain mathematical breadth, drawing on the extensive range of PGR taught units, including the Bath-Bristol-Imperial-Oxford-Warwick Taught Course Centre to which the UoA contributes 90+ lectures per year, the Academy for PhD Training in Statistics in which the UoA is an Underwriting Member, and courses delivered by the CDTs. They attend at least one weekly seminar and present their own research annually. PGRs are allocated a Research Training Skills Grant, typically £1000 per year, which supports conferences, academic visits, and other research expenses, with the expectation of presenting at least one overseas meeting during their studentship. The UoA operates rigorous Annual Progress Monitoring for each PGR, overseen by the Director of Postgraduate Research and Graduate Dean. There are three dedicated administrators for PGR student affairs and CDT activities. PGRs are assigned a designated pastoral supervisor, separate from their primary supervisory team. Wellbeing is addressed throughout, in close collaboration with the UoB's wellbeing team. In 2018 UoB created a hub to provide front-line service to PGRs, and additional support and links to the wider research environment is provided by the Bristol Doctoral College (BDC, see 2.24, REF5a).

2.23 PGRs organise an annual one-day conference at the beginning of the academic year, MINGLE, where each student beyond the new starters presents their research. They also run a weekly seminar series spanning all branches of mathematics. The UoA's PGRs organised in 2014 (and scheduled for 2020 but postponed until 2021) the annual UK Young Researchers in Mathematics conference, which attracts over 200 attendees. Many PGRs are actively involved in outreach and public engagement activities such as workshops in local schools and science festivals (see 4.7). The UoA financially underwrites all these activities.

## Unit-level environment statement (REF5b)

2.24 A broad suite of training is available from the BDC's Personal and Professional Development programme (REF5a), notably including six half-day events on communication, media training, industrial relationship building, and presentation skills. The BDC also funds innovation and leadership development and facilitates the annual postgraduate conference, *Research without Borders* (see REF5a). UoA senior staff deliver a bespoke lecture series on mathematical research skills. PGRs who teach are given mandatory teacher training. The UoA CDTs deliver training in ethics and responsible innovation (see 1.25). Computational skills training is available from the Advanced Computer Research Centre (ACRC). Our PGRs are well prepared for future careers: during the REF period, approximately 50% have moved to postdoctoral appointments, over half of which of which are overseas, while other careers have included teaching, finance and industrial research and development.

## Equality and diversity

2.25 The UoA's is committed to creating an inclusive environment where diversity is valued, and people of all characteristics are supported and encouraged to fulfil their potential. This commitment permeates all aspects of our research and staffing strategies (see 2.2-2.10); notably, the UoA's track record in promoting gender equality in mathematics was recognised by an Athena SWAN Silver Award in 2018 (Bronze, 2014), one of only 8 mathematics departments to hold an award at this level. Two co-Directors of EDI (**Ganesh** and Machin), one academic and the other professional services staff, maintain oversight with the UoA EDI Committee, which meets four times per year and contains representatives from permanent academic, postdoctoral, postgraduate and professional services staff, as well as members with a focus on ethnicity, gender, disability and LGBT+ identities. The Committee's recommendations have had measurable impacts upon the UoA's operations, such as recruitment procedures (see 2.2 and note the increasing gender and ethnicity balance in UoA staff) and introducing a numerical target for the proportion of female speakers at seminar series and conferences organised within the School, which has led to a doubling in their number. (The new target from 2019 is 30%.) Ethnic diversity is also addressed with UoA commitments to monitor recruitment and from June 2020, to review curricula and introduce a target proportion of BAME speakers at colloquia.

2.26 The diversity of the UoA senior management committee has grown during the assessment period, with the proportion of those with protected characteristics rising from 40% in 2014 to 54% in 2020.

2.27 We promote a diverse research culture, including hosting the national event, *Women and Non-binary People in Mathematics: Opportunities for the Future* (see 2.19). We introduced a Code of Conduct to prevent harassment based on protected characteristics, to which all participants at UoA-organised events are required to sign up. We have introduced mandatory Bystander Training to help staff recognise and respond to inappropriate behaviour in the workplace and maintain an inclusive working environment. UoA social events are inclusive of part-time staff and children and other dependents are invited; they are family-friendly, for example by choosing appropriate venues and entertainment. Furthermore, the Fry Building was designed to support staff and students with protected characteristics (see 3.5).

2.28 The UoA has an agile research culture and is supportive of academic staff and PGRs remote working when appropriate. Formal flexible or part-time working arrangements can be requested, and staff with caring responsibilities can avoid lectures at either 9am or 5pm. It is UoA policy to keep meetings within core hours whenever possible, and to record public talks or other events unavoidably held out of hours. Parental leave is managed through a combination of

## Unit-level environment statement (REF5b)

initiatives including Keep in Touch Days, Maternity Mentoring and a Returning Carers Scheme – the latter allows staff to claim up to £10k for expenses to support their return, including buying out teaching commitments – and sabbatical credit is earned during maternity leave. Additionally, a UoA-specific factsheet for parental leave gives practical information on support offered by UoB, and UoA parental mentors. Staff may claim from the UoA exceptional expenses for childcare or other caring duties arising from conference attendance, and we have chosen to fund eligible caring costs for visiting staff and students attending many of our own events. The UoA also hosts weekly lunches for Women and Non-binary staff and PGRs to provide opportunities for the exchange of ideas and experiences. The UoA intranet provides a portal to comprehensive information on equality, family and work balance and mentoring.

### Well-being

2.29 All staff and PGRs may access UoB's well-being resources and there are 30 mental health champions to raise awareness and tackle institutional stigma. During the COVID-19 closures, several initiatives were introduced and extended to maintain well-being, including a 24-hour employee assistance programme, coaching, mental health awareness weeks and virtual mindfulness sessions. Additionally, the UoA convened many additional virtual staff meetings to maintain contacts and community while working from home.

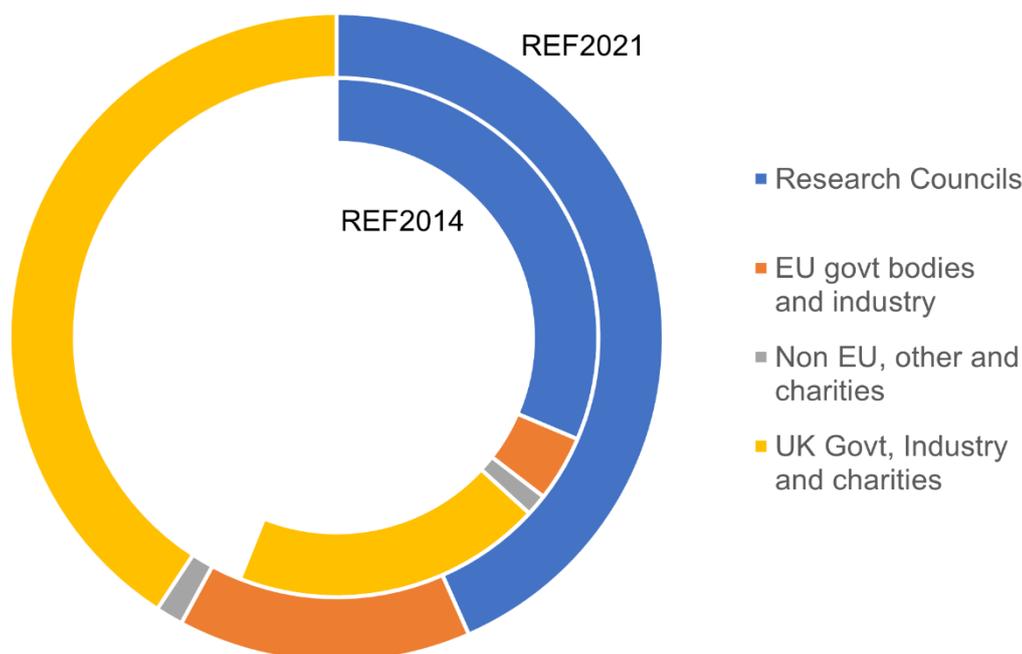
### REF submission EDI strategy

2.30 The UoA has adhered rigorously to UoB's Code of Practice for REF submissions, which embodies the four principles of transparency, consistency, accountability, and inclusivity. All UoA staff involved with REF decision-making received mandatory training on EDI and unconscious bias; the composition of the UoA REF committee was formally approved by the UoB Research Committee. Staff eligibility for REF submission was determined through a transparent process, run by the UoB Research Committee, while the disclosure of staff circumstances to an independent group has been voluntary and confidential. Potential research outputs were assessed by at least two independent reviewers, whose judgments were calibrated through initial training. We ensured that our submission includes contributions from ECRs and that interdisciplinary work is represented. Our final choices were cognisant of the distribution of outputs across staff and their protected characteristics, choosing those from under-represented characteristics if similarly ranked.

## 3. Income, infrastructure and facilities

### Research funding strategies

3.1 The UoA has had exceptional success in securing funding for research, with our HESA-reported income rising to £33.2M (excluding support for CDTs), a 27% per annum increase from REF2014 (see Ref4b and figure 3). Our enabling strategies have included (see 2.9,2.13): (i) re-balancing workloads to allow the construction of high-quality proposals; (ii) replacement teaching for fellowships and secondments; (iii) flexibility to concentrate teaching in one semester; and (iv) UoA support mechanisms during the application process. These UoA strategies, coupled with the accommodation of flexible working patterns, underpin increased diversity in the funded portfolio by removing barriers to accessing research support and preparing applications.



**Figure 3: External funding by source. The REF2021 total (£33.2M) is a 27% per annum increase from REF2014.**

3.2 The funded portfolio spans mathematical science and features major awards in our areas of strategic growth and strategic alliance with GCHQ, including probability, data science and number theory. Research council awards include EPSRC Programme Grants (**Andrieu, Booker, Keating, Kerswell, A. Lee\*, Wiggins**) and other large grants (e.g. **Dokchitiser, Dettmann, Andrieu**). UoA staff have won many competitive fellowships, including 8 ERC fellowships (Advanced: Keating, **Marklof**, Wooley; Consolidator: **Montanaro\***; Starting: Russo, Ulcigrai, Gorodnik, Browning), 8 EPSRC fellowships (Advanced Career: Wood; Established Career: Nason, **Toth**; New Directions: **Booker**; Early Career: **Montanaro\***, Mohammadi, Brooke-Taylor; Postdoctoral: Pawlowski), 3 Royal Society fellowships (University Research Fellowship: Russo, **M. Lee\***; APEX: **Hogg**), 3 Leverhulme fellowships (**Eggers, Grava, Maltsev**), 2 Vice Chancellor's fellowships (**Bennett\*, Maciazek\***), 3 Marie-Curie fellowships (Le Masson, **Schlicht\***, Sahlsten), Japan Society for the Promotion of Science (JSPS) fellowship (**Liu\***), WT SHD fellowship (**Lawson\***) and 4 UoB Research fellowships (Leslie, **Mezzadri, Robbins, Walling**).

### Organisational Infrastructure

3.3 Interdisciplinary research and impact activities are facilitated by the URIs and SRIs, who assist and coordinate major bids (see 1.22). RED provides expert support, particularly with UoA's applications for ERC fellowships, EPSRC CDTs (two from the UoA reached the final stage of the last round) and the renewal of HIMR. RED also coordinate the distribution of EPSRC IAA funds (the UoA received 8 awards, totalling £191K, see 2.17,2.18 for examples) and QR-Global Challenges Research Fund (**Hogg**).

3.4 This infrastructure enables two distinctive aspects of our funding profile: (i) As HIMR's core academic partner, we receive substantial funding from GCHQ, which enhances our research environment and extends the impact of our mathematical research. (ii) Our staff collaborate widely with other academic disciplines (see 1.22,1.23), and have been co-investigators in several large, multi-institutional consortia. Examples of this activity include: Quantum Computing (Google Prosperity Partnership, £5.5M, Quantum computing and simulation hub, £24M), Synthetic Biology

## Unit-level environment statement (REF5b)

(BBSRC: BrisSynBio, £14M) and environmental science (NERC: VANAHEIM, £2.7M, STREVA, £2.7M).

### Research infrastructure

3.5 Our REF2014 submission, and its forerunner in RAE08, anticipated the move to a new building. Completed in 2019 after a 4-year redevelopment at a cost of £33M, the Fry Building is the iconic new home for mathematical sciences in Bristol, demonstrating significant institutional support for the discipline. The interior space was reimaged and repurposed through intensive collaboration between architects and senior UoA staff. The Grade II-listed Victorian building provides vastly more space (4500m<sup>2</sup>) than our previous home, reflecting not only the enduring popularity of our undergraduate programme (admissions increased over 74% during the past decade), but also our ambition to address new research areas that supplement and complement our existing expertise (see 1.17). The space beautifully serves the varied needs of the mathematics community – co-location of research institutes with PGRs; large staff common room providing a forum for informal interactions and school meetings; blackboards in offices and common areas, alongside contemporary IT infrastructure; space to host visitors and international symposia (see 4.4,4.5); and engineered accessibility to meet the needs of staff with protected characteristics. The Fry Building has already had a profound effect on mathematics in Bristol.

3.6 All members of the UoA have charge-free access to excellent research computing facilities and infrastructure, delivered through two major facilities:

- i. The UoA runs its own Intermediate Performance Computing farm (CREAM: Cluster for REsearch in Advanced Mathematics), which totals 332 cores (including 4 GPU nodes) and is maintained by UoB specialist staff. During the REF period, CREAM has been expanded and maintained through UoB investment (£74K). CREAM provides an invaluable tool for medium-scale computations and code-testing. Additionally, the UoA has begun to migrate computational tasks of this scale to a new state-of-the-art facility (Blue Pebble) for high-throughput computing, supported by the ACRC (UoB).
- ii. UoA staff access high performance computing facilities through UoB's high-performance BlueCrystal Phase 3 and 4 clusters. Following a further investment (£16M during the past decade), Phase 4 now has more than 16,000 cores and a theoretical peak performance of 617 Teraflops, which at launch was ranked 398 among the world's top 500 fastest computers (June 2017).

3.7 There is secured, long-term data storage systems for personal and research data (5TB free for each project). Also, funded via an EPSRC equipment call, the UoA purchased a high-resolution 3D printer (£80K), which has been used, for example, to prototype the energy surface of the dissociation of ozone for research and public engagement purposes (**Wiggins**).

3.8 Members of the UoA have made extensive use of these computational facilities. Notably, they underpinned programme grants awarded to **Wiggins** (see 1.14); **Booker & Keating** (computational number theory); and **Andrieu** (computational statistics). Moreover, the provision of high-performance computing underpins our strategic expansion in data science, artificial intelligence, cybersecurity and big data (**Allison\***, **Lawson\***, **Rubin-Delanchy\***, **Liu\***, **A. Lee\***); algebra, group theory and representation theory (**Burness**, **Dokchitser**, **Harper\***); and number theory (**Booker**, Platt, **Kopp\***).

## Unit-level environment statement (REF5b)

3.9 Members of the UoA access national and international facilities for large-scale computation. **Linden, Liverpool** and collaborators in chemistry engaged 6 months of time on ARCHER to successfully analyse the assembly of peptide nanocages; **Booker** (with Sutherland, MIT) utilized cloud computing, via Google Compute Engine and Charity Engine, to show that 3 can be expressed as the sum of three cubes, amongst other number theoretical challenges; and **Linden** and **Montanaro\*** are in a partnership to develop software for Google's quantum computer, research which will translate into applications with key industrial partners.

## Scholarly and operational infrastructure

3.10 UoA research is enabled by sustained institutional provision and investment in its physical infrastructure.

- i. The UoB library hosts an extensive collection of research texts and journals (with free-to-use online access). There is ongoing work to redevelop its physical location (£80M).
- ii. UoB is building a new campus in the centre of Bristol (TQEC, see REF5a), which will host the new Quantum Technology Innovation Centre (see 1.21iii).
- iii. Several UoA staff collaborate with UoB experimental groups. For example, laboratory capacity in Chemistry underpins **Eggers's** collaboration on colloids and gels (3 outputs during assessment period), and laboratory capacity in Biology underpins **Chenchiah's** £838k BBSRC grant on biophysics of electroreception in arthropods.

## Professional Support

3.11 Outstanding professional support for research is provided by a large UoA team based in the Fry Building. These include staff for postgraduates (3.5FTE), KE (1FTE), conferences (1FTE), facilities (1FTE), HIMR activities (4.2FTE) and other research administration (1.5FTE). There have been over 75 workshops and conferences organised by this team during the assessment period, including 37 with significant international participation. Examples include Quantum Computing Theory in Practice (2019), International Workshops on Statistical Modelling (2018) and Water Waves and Floating Bodies (2015), in addition to British Mathematical Colloquium (2016), PAD (2014,2018, see 1.4) and the annual HIMR Conference (see 4.2). Further support is provided by the UoB Finance and Contracts teams, with a dedicated officer for Mathematics; public engagement specialists; and teams that support international staff and wellbeing (see REF5a). RED include a dedicated impact team, with an officer assigned to the science faculty alone, and expert advice on commercialization to support patents (e.g. for **Linden**, granted 2017) and startups (Phasecraft, **Montanaro\***, 2018, see 2.18).

## International and national facilities

3.12 UoA researchers engage with national research institutes (e.g. HIMR and ATI). UoA staff have organised and/or participated in long-term visitor programmes at the UK's Isaac Newton Institute and the International Centre of Mathematical Sciences, and internationally at centres including the Mathematical Sciences Research Institute (MSRI), Kavli Institute for Theoretical Physics (KITP), and Banff International Research Station (BIRS). The UoA strongly encourages and facilitates staff to join these programmes, re-organising duties and underwriting travel and subsistence costs (see 2.14). A complete list of the UoA's involvement is given in 4.12.

## Unit-level environment statement (REF5b)

### Third stream funding

3.13 During the assessment period, philanthropic funding for UoA research infrastructure and the Fry Building was secured from the Wolfson Foundation and others (£900k). In addition, the UoA received benefits in-kind through partnerships and grants (e.g. external support of £2.4M for COMPASS CDT and £2.2M for Google Prosperity grant), support for secondments (see 2.17) and CASE studentships. We also secured alumni funding for an innovative programme of summer research-project bursaries for talented undergraduates from under-represented groups, providing these students with a first-hand experience of research mathematics.

### COVID-19 Support

3.14 The UoA was cognisant of the challenges of working from home during the COVID-closures, providing computational facilities and office furniture when needed, as well as being early adopters of virtual means for maintaining research collaborations. When it became possible to reopen the Fry Building, extensive safety measures were emplaced and access was prioritised for those without adequate home-based facilities.

## 4. Collaboration and contribution to the research base, economy and society

### Strategies for enabling collaborations

4.1 The UoA has sustained a collaborative and outward-looking ethos through strategic partnerships, secondments and interdisciplinary research and have been partners in multi-institution consortia and programme grants (see 1.5, 1.22, 1.23, 2.17, 3.4). Some outputs of these activities are part of our REF submission, particularly the impact case studies arising from our partnership with GCHQ. Collaborations are facilitated through several strategies: (i) underwriting all travel grant applications and no reasonable request goes unfunded; (ii) supporting external collaborators who come to Bristol, often for long stays, both financially and through visitor space in the Fry Building; and (iii) encouraging fellowships to free up research time and undertaking secondments (see 2.9, 2.17, 3.2). In addition, Science Faculty and start-up funds for new appointments, UoB International strategic funds (UoA recipients: **Chenchiah, Cho, Robbins, Wiesner**) and support from the URIs are used to pump prime new collaborations.

4.2 The partnership with HIMR provides a significant mechanism for building research collaborations and networks. During the assessment period in Bristol, there have been 11 HIMR Colloquia and 24 other events, which regularly feature leading international researchers. For example, Perspectives in the Riemann Hypothesis (2018) featured lectures by Fields Medallists Bombieri, Connes and Tao. The UoA hosted 12 Heilbronn Distinguished Lecture Series featuring world-leading mathematicians, for example Daubechies (Duke), Sarnak (Princeton), Williamson (Sydney) and Ellenberg (Madison). The Heilbronn Annual Conference, a Bristol-hosted two-day annual meeting, features eminent speakers (e.g. Wiles (Oxford) and Hairer (Imperial)) and attracts a large number of attendees (100+) from within and outside the UoA.

4.3 Through participation and theme-leadership in ATI, UoA staff received research funding, supervised PGRs, convened international workshops and helped shape the national agenda for data science. The UoA's data science activities are co-ordinated with JGI, which together with HIMR funds research collaborations and supports the new Data Science seminar (see 1.15).

## Unit-level environment statement (REF5b)

4.4 The UoA funds 16 seminar series that span mathematical sciences and a school-wide colloquium, featuring internationally-distinguished speakers, including, for example, Bird, Goldstein, Babai, Silverman and Villani. Through these events, UoA members engage with researchers at the forefront of their fields, while providing indispensable networking opportunities for our ECRs.

### Visitors

4.5 A vibrant visitor programme is essential for the vitality of the environment. We have invited and hosted over 900 visitors during the assessment period, approximately half of whom are from overseas. Several international visitors have won competitively-awarded UoB's Benjamin Meaker Professorships, which fund research periods of up to 3 months in Bristol. Mathematicians who have received these visiting professorships include Farantos (Crete, 2014), Peyre, (Grenoble, 2016), Ungarish (Technion, 2017), Smith (Wellington, 2018), Bogomolny (Paris-Sud, 2018) and Martelli (IBM, 2018). There are two further strategies for enabling mathematical collaborations: (i) HIMR Focused Research Grant scheme, for fostering adventurous and ambitious research between small groups of participants (18 events in Bristol). (ii) the UoA established a Heilbronn Distinguished Visitor programme with dedicated schemes for data science (e.g. Priebe (Johns Hopkins); Samworth (Cambridge); Huggins (MIT)) and pure mathematics and mathematical physics (e.g. Rudnick (Tel Aviv), Liverani (Rome), Feng (Hong Kong)).

### Engagement with beneficiaries

4.6 Our strategy for engagement with end-users of research is set out in 2.16-2.17 and is identical to support for academic collaborations. The UoA provides financial underwriting, frees staff time and accounts for activities in the workload model. Examples of our global engagement include the Farmer Business Network (FBN) & EDF, who employ generalised additive models developed by Wood & **Fasiolo\***. Predictions by FBN, allow their 7000 member farms in USA and Canada, which cultivate over 23 million acres, to increase revenue by US\$23 per acre. EDF utilise the statistical methodology to forecast energy demands operationally, saving the company costly over- or under-production. **Wiesner's** collaboration with the Green Climate Fund, a new global fund created to support the responses of developing countries to climate change, has co-produced an evaluation of its strategic methods, using complex systems theory. **Lawson\*\***'s population genetics tool, FineStructure, has been licenced to LivingDNA and forms the core of their commercial ancestry test from over 100 British and worldwide populations.

4.7 The UoA is actively participating in public engagement, with a focus on communicating research to inspire the next generation of mathematicians and forming closer links with local schools that have little engagement with higher education. The UoA Director of Public Engagement (**Erlandsson\***) coordinates these activities, a role supported by the University Centre for Public Engagement, who provide bespoke training for mathematics projects. We have presented research at national science fairs, including the Big Bang Fair (2017, Exeter and Bristol; 2018 Weston), NERC's Into the Blue showcase (2016, winning the public vote for the best exhibit), Pint of Science events in Bristol (2016-18) and established a public lecture series. We have conducted numerous workshops in local schools, recorded several videos for the Numberphile YouTube channel and instigated Creative Reactions (2019), a collaboration between artists and scientists, featuring nine members of the UoA and culminating in a month-long gallery exhibition. **Wiesner's** innovative research of complexity in physical and social systems has featured in podcasts (Sean Carroll's Mindscape and Physics World Weekly), a TEDx talk and in a book, 'What is a complex system?', co-authored with Ladyman (Philosophy). The UoA has had outstanding success in the high-profile

## Unit-level environment statement (REF5b)

House of Commons *STEM for Britain* poster competition, with two gold medals (Platt, Maistret) and one bronze (Naskrecki) during the census period, the best record of any UK mathematics department.

## National and International Leadership

4.8 Members of the UoA serve and lead the broad community of mathematical sciences in several ways:

- i. **Journals:** 7 roles as main/managing editor including Annals of Applied Probability (**Toth**), Statistical Science (**Green**), J. Group Theory (**Burness**), J. Royal Statistical Society B (Wood) and from 2021, Probability Theory and Related Fields (**Toth**). Additionally, 27 UoA members are Associate Editors for 39 journals that broadly span mathematical science including Annals of Applied Probability (**Ganesh**), Communications in Mathematical Physics (**Marklof**), Entropy (**Wiesner**), J. Machine Learning Research (**A. Lee\***), J. Number Theory (**Booker, Conrey**), Nonlinearity (**Grava**), Physical Review Letters (**Eggers**), Physica D (**Grava**), Statistics and Computing (**A. Lee\***, Wood) and Wave motion (**Porter**).
- ii. **Funding councils and professional bodies:** Twelve staff of the UoA have been members of the EPSRC College, while one was a member of the NERC College. **Hogg** and Keating served as committee members for the EPSRC Review of Knowledge Exchange in Mathematics and several have participated in EPSRC Mathematics Prioritisation Panels. **Andrieu**, Nason and Wood have held substantial leadership roles with the Royal Statistical Society; **A. Lee\*** is the director of the Data Science and Artificial Intelligence At Scale initiative of the ATI; Nason held advisory roles with National Statistics Advisory Group and the Departments for Education and Business, Energy and Industrial Strategy; and Rougier was the Scientific Advisor to Cabinet Office (2016). **Dokchitser** has served on grant and fellowship awarding committees of the Royal Society and **Toth** has chaired the committee of the Bernoulli Society that oversees conferences on stochastic processes, as well as being a jury member for Institut Universitaire de France (mathematics) and a member of the ERC mathematics panel. **Conrey** is the executive director of the American Institute for Mathematics; Keating is the president of the London Mathematical Society. **Linden** and **Montanaro\*** are part of the leadership team of the National Hub for Quantum Computing (see 1.23ii)

## Learned societies, Fellowships and Prizes

4.9 During the assessment period **Marklof** (2015) was elected as a Fellow of the Royal Society joining **Green**, Keating, Kerswell, McNamara, Wooley. **Toth** was elected to Academia Europaea (2016) and **Eggers** as a EUROMECH Fluid Mechanics Fellow (2014). **Eggers** is a Fellow of the American Physical Society and **Conrey, Walling** and Wooley are Fellows of the American Mathematical Society. Several school members have won competitively awarded fellowships (see 3.2) and been awarded Royal Society Wolfson Awards (**Eggers**, Keating, Kerswell, **Holroyd\***).

4.10 Staff in the UoA have been awarded the following prizes: Whitehead Prize: **Montanaro\***; Frohlich Prize: **Mezzadri**; Stanley Corrsin Award APS-DFD: **Eggers**; LMS Anne Bennett Prize: Wolf; Leverhulme Prize: Russo, Ulcigrai; Young Scientist Award in Statistical Mechanics and Thermodynamics (Royal Soc. Chemistry): Russo; Early Career Institute of Physics: Liquids and Complex Fluids **Bennett\***; Marychurch Award for Cryptoanalytic Excellence, **Crane**; Hamlos-Ford Award (Math. Assoc. America), **Holroyd\***; Gábor Szegő Prize, **Bothner\***; Suffrage Science Award: **Snaith**; SIAM Student Paper Prize: **Kopp\***.

## Unit-level environment statement (REF5b)

### Keynote Lectures and Conferences

4.11 Amongst the many invited contributions by UoA staff to international conferences, the following are some of the most prestigious keynote and plenary presentations: International Congress of Mathematics (**Marklof** 2014, Wooley, 2014; **Toth** 2018); American Physical Society: Division of Fluid Dynamics (**Eggers**, 2017); Hanna Neumann Lecture (Australian and New Zealand Mathematical Societies, **Snaith**, 2014); International Congress on Number Theory and Physics (Keating 2015).

### Visitor and PGR-training programmes

4.12 UoA staff frequently participate in international academic visitor programmes and the UoA supports their involvement through sabbatical leave and travel costs. During the REF period, staff have participated in programmes at Isaac Newton Institute for Mathematical Sciences (INI), BIRS, International Centre for Mathematical Sciences (ICMS), Mathematical Sciences Research Institute (MSRI), Mathematisches Forschungsinstitut Oberwolfach, Institut Henri Poincare, Max Planck Institutes for Mathematics and for Complex Systems, Fields Institute and Clay Mathematical Institute. Notably **Andrieu & Slastikov** were programme organisers at INI (Scalable Inference, 2017 & Mathematical Design of Materials, 2019, respectively), Wolf at Simons Institute (Pseudorandomness, 2018), and **Grava** held the Jean-Morlet Chair, CIRM (Integrability and Randomness in Mathematical Physics, 2019). UoA staff have also contributed to several international PGR training workshops; some examples Institut d'Etudes Scientifique de Cargese, (Wave propagation in complex media, **Porter**), MSRI (Geometric group theory, **Mackay**), Les Houches, Summer School (Stochastic processes and random matrices, **Tourigny**) and Saint Flour Probability Summer School (**Toth**).