

Institution: University of Birmingham
Unit of Assessment: UoA10, Mathematical Sciences
<p>1. Unit context and structure, research and impact strategy</p> <p>1.1 Overview and unit structure</p> <p>Mathematics is one of seven schools in Engineering and Physical Sciences, one the University's five Colleges. The UoA has transformed in scientific breadth and external engagement over the assessment period, building significantly on recognised strengths in Combinatorics, Analysis, Algebra and Optimisation. Substantial institutional investment supports new inter- and intra-disciplinary research in Mathematical Biology and Healthcare, Geometry and Mathematical Physics, and Topology and Dynamical Systems. The UoA has grown to 57.2 FTE at census (from 40 in REF2014). It has held/secured 21 fellowships and personal awards in the assessment period, encompassing extremal combinatorics, algebraic geometry, representation theory, biological fluid dynamics, and mathematical neuroscience. The UoA hosts recipients of prestigious awards including three LMS Whitehead Prizes, three European Prizes in Combinatorics, and a Philip Leverhulme Prize. Alongside recognised strength in theoretical foundations, we support interdisciplinary initiatives, for example by co-leading the £10.5M cross-university Centre for Systems Modelling and Quantitative Biomedicine (SMQB).</p> <p>The UoA is broadly structured around Pure and Applied Mathematics. Many interactions between these areas, for example the Mathematics Colloquium and regular joint seminars, enable staff to share ideas, fostering a collaborative atmosphere. The unit structure is as follows (<i>staff/student numbers are at census date unless otherwise indicated</i>):</p> <p>Pure Mathematics (31 FTE, 48% growth since REF2014):</p> <ul style="list-style-type: none"> Algebra (5 FTE + 1 post-census appointment; 1 PDRA; 10 PGRs): finite group theory, representation theory. Analysis (10 FTE; 1 PDRA; 5 PGRs): key strengths in harmonic analysis, PDEs, geometric measure theory, functional analysis. Combinatorics, Probability and Algorithms (10 FTE; 5 PDRA; 10 PGRs): extremal combinatorics, connections to topology, statistical physics, probability and design theory. Geometry and Mathematical Physics (2 FTE + 3 post-census appointments; 3 PDRA; 2 PGRs): integrable systems and algebraic geometry, linking with algebra via representation theory. Topology and Dynamical Systems (4 FTE; 2 PGRs): topological dynamics, aperiodic order, fractal geometry, measure theory, number theory. <p>Applied Mathematics (26.2 FTE, 38% growth since REF2014):</p> <ul style="list-style-type: none"> Mathematical Biology and Healthcare (9.2 FTE; 11 PDRA; 9 PGRs): mathematical neuroscience, biological continuum mechanics, systems biology, biological networks. Nonlinear Systems and Continuum Mechanics (6 FTE; 3 PDRA; 5 PGRs): bubble dynamics, free-surface hydrodynamics, industrial applications. Optimisation, Numerical Analysis and Statistics (11 FTE + 1 post-census appointment; 2 PDRA; 14 PGRs): conic optimisation, uncertainty quantification, mathematical ecology and epidemiology, clinical trial design. <p>Highlights during this assessment period include:</p> <ul style="list-style-type: none"> - Major theoretical advances, e.g. Csaba, Kühn, Lo, Osthus and Treglown's proofs of the <i>1-Factorization and Hamilton Decomposition conjectures</i>, dating back to the 1950s and 1970s respectively; Glock, Joos, Kim, Kühn and Osthus's proof of the

Oberwolfach Conjecture (posed in 1967); Good and Meddaugh's discovery of deep connections between *shifts of finite type* and *shadowing*.

- **Major global impact** via the widespread adoption of Kocvara's Conic Optimisation project *PENNON* and the software *PENCOR*, used by Allianz to manage risk in over €23B in funds.
- **A three-fold increase in research income** from £3.3M in REF2014 to £10.1M in REF2021.
- **Significant investment in staff**, including 28.2 new FTE, and improved retention and promotion of 22 outstanding early-career researchers and 4 senior leaders, growing the UoA from 40 to 57.2 Category A FTE this cycle.
- **Establishing the Jinan University–University of Birmingham Joint Institute (JBJI)**, supporting investment of 17 new FTE and 6 RAs to the UoA (10 this cycle).
- **Increasing staff diversity and leadership**; 22% of Professors and Readers are female, up from 7% in REF2014.
- **Increasing PhD awards by 20% per annum.**

1.2. Research strategy

The UoA's research vision is built on five strategic aims:

1. Build on existing strengths, introduce new strategically important areas and enhance cross-theme collaboration

REF2014 recognised the UoA's world-leading and internationally excellent outputs. Existing strengths have been significantly expanded in line with REF2014 aims for Analysis, Combinatorics and Mathematical Biology (Sec.1.3).

In addition, significant investment in new areas at the interfaces of our strengths add to the vitality and sustainability of the UoA, including Healthcare (broadening Mathematical Biology, including SMQB) and Topology (3 new FTE, building on Good's successes). Recent appointments (e.g. Carmesin, Duong, Shang, Terry) enhance connectivity between themes (Sec.1.3).

2. Strategic development of impact and a culture of translational research

Targeted support, including funding and mentoring, has enabled growth in translational research. All Impact Case Studies are the result of proactive support for academics, while two 3-year research associateships highlight investment in promising new translational areas of high impact. Three early-mid-career academics (Dyson, Jabbari, Petrovskaya) were assisted in early-stage impact development in fluid dynamics in plant sciences, modelling of antimicrobial resistance, and numerical analysis in pest monitoring. This led to Dyson and Thomas-Seale's (Engineering) record of invention for the GrowCAD plant growth-inspired additive manufacturing methodology, Jabbari's joint £180K Leverhulme project with Fernandez-Trillo (Chemistry), and six outputs led by Petrovskaya with Harper Adams University on pest monitoring and control in agriculture. The UoA has also benefitted from institutionally managed funds: the EPSRC Impact Acceleration Account supported Reguera's Developing Leaders award and funded D. Smith and Jabbari's work with Procter and Gamble on model parameter estimation improving detergent formulation, leading to subsequent financial investment from P&G.

3. Establish and sustain research that confronts challenges in other disciplines

Recognising the importance of mathematics to other disciplines, we have taken a systematic approach to establishing and sustaining **interdisciplinary research**.

Interdisciplinary Research Officer Spill creates and maintains connections across the University and beyond. Knowledge Exchange Lead Montenegro-Johnson convenes workshops to initiate projects with industry and government bodies.

The UoA participates in the multidisciplinary University Institute for Global Innovation (2.3-REF5a), notably *Confronting Antimicrobial Resistance* (Jabbari) and *Water Challenges* (Tzella), and the Birmingham Institute for Forestry Research (Dyson). Staff hold honorary positions in the Centre for Computational Biology, Centre for Topological Design, Institute for Metabolism and Systems Research, Institute of Microbiology and Infection, and Institute of Translational Medicine. We actively develop interdisciplinary links with industry, as exemplified by recent collaborations with Ultrahaptics and Cellink (Montenegro-Johnson), Alphasonics (WR Smith and Q Wang), and Phytoponics (Dyson). We participate in interdisciplinary doctoral training including the EPSRC Topological Design CDT, Wellcome Trust Mechanisms of Inflammatory Disease, Wellcome Trust Antimicrobials and Antimicrobial Resistance, MRC Integrated Midlands Partnership for Biomedical Training, BBSRC Midlands Integrative Biosciences Training Partnership, Centre for Complexity Science (Warwick). These have collectively led to numerous interdisciplinary publications (e.g. Kerr et al. *Access Microbiol.* 2020; Ziegler et al. *Interface* 2019; Hall-McNair et al. *Phys. Rev. Fluids* 2019; Klaise *Phys. Rev. E* 2018).

We co-lead the Centre for Systems Modelling and Quantitative Biomedicine (SMQB) (£7.8M internal investment, £2.7M from Epilepsy Research UK, NIHR and the Wellcome Trust ISSF), forming a multidisciplinary initiative spanning Mathematics, Computer Science, and Metabolism and Systems Research. SMQB leverages strengths in mechanistic modelling, institutional investments in Healthcare Technologies and strategic connections with University Hospitals Birmingham (2.1.3-REF5a and Sec.1.3, 3.2 below). To foster interdisciplinary research in data science, the University joined the Alan Turing Institute in 2018; four members of the UoA (Bespalov, Fountoulakis, Johnson and D. Smith) hold Turing Fellowships (Sec.3.2).

4. Increase external and internal investment to support world-leading research activities

A range of mechanisms support grant capture (Sec.3.1), including travel funds for project development, peer review, interview coaching, PhD scholarships, and reduced teaching to provide time for funding applications and project delivery. Fourteen staff, including a subsequent UKRI Future Leaders Fellow (FLF), attended the College's Grant Writing Series.

Research income in this REF cycle totals more than £10.1M, trebling the REF2014 figure. Funding from research councils has grown 208%; from EU sources 313%; from charities 176%. Forty-three staff received external funding; women (17.5% of staff) secured 27.2% of this income. This funding supports academic staff through personal fellowships and PDRAs/PGRs, contributing to the vitality of our research environment.

Institutional investment has supported growth from 40 to 57.2 Category A FTE this cycle (rising to 62.2 at March 2021).

5. Ensure the best researchers are hired to deliver our research strategy

Since 2014, we have recruited from Oxford, Cambridge, Warwick, Imperial, ETH and MIT. Seven appointees have received personal awards of over £1M, e.g. Carmesin's EPSRC Fellowship, Kelly and Spill's UKRI FLF, and Montenegro-Johnson's Leverhulme Research Leadership Award; post-census hires Closset and Topley hold major fellowships (RS University Research Fellowship and UKRI FLF).

Actions highlighted in our Athena Swan Bronze Award (2018-22) show demonstrable impact, with the appointment of three new female staff (Kombrink, and two post-census appointments Peon-Nieto and Touloupou). Advertising on the 'Out in Math' Facebook page

resulted in at least one lectureship appointment this cycle.

1.3. Achievements and future aims by theme

Our REF2014 submission outlined goals of (i) growing Algebra, Analysis, Combinatorics, Nonlinear Systems, and Biomathematics, (ii) the continued development of outward-facing research in Optimisation and Statistics, and (iii) strengthening the interface between Data Science and Medicine, with a focus on impact. Both Analysis and Combinatorics have grown from 6 to 10 FTE and Mathematical Biology (including SMQB) from 3 to 9.2 FTE, with a number of appointees already holding prestigious personal awards. Optimisation and Statistics have grown to encompass optimisation for data science and areas at the interface with medicine and life sciences. SMQB provides a cross-university structure supporting interdisciplinary research and impact. Algebra, Continuum Mechanics and Nonlinear Systems have maintained excellent research activity; growth in these areas has primarily been through appointments in closely related areas (e.g. Geometry, Mathematical Biology).

Combinatorics, Probability and Algorithms

Led by Kühn and Osthus (LMS Whitehead Prize 2014, invited ICM speakers 2014), this theme is recognised as one of the world's leading Combinatorics groups. Achieving a REF2014 aim, it has expanded to 10 permanent staff (from 6 in 2013). This includes three Birmingham Fellows (3.4.1-REF5a) appointed from Cambridge: Lo (2014); Montgomery (2018, recipient of the 2019 European Prize in Combinatorics); and Carmesin (2018). Carmesin expands activity to include topological and structural graph theory, resulting in wider interdisciplinary collaboration, e.g., through supervision in the CDT in Topological Design. Jenssen (from Oxford) works at the interfaces of combinatorics, statistical physics and computer science; Long (Oxford) in extremal and probabilistic combinatorics.

Eighteen major awards held this cycle include two EPSRC Fellowships (Kühn, Treglown, additionally Carmesin post-census); an ERC Advanced Grant (Kühn); ERC Starting Grant (Osthus, additionally Montgomery post-census); three EPSRC First Grants (Lo, Mycroft, Perkins); RS Wolfson Research Merit Award (Kühn). Montgomery won a Philip Leverhulme Prize post-census. Nineteen postdocs also added to the vitality of the group this cycle (five previous cycle).

2021-26 Objectives: To focus on interactions between probability and combinatorics, with the goal of developing a toolbox for attacking extremal questions in combinatorics, including for perfect matchings and graph decompositions. Work at the interface with theoretical computer science, emphasising randomised algorithms for large networks and other discrete structures.

Mathematical Biology and Healthcare

In 2014, Mathematical Biology consisted of three recent appointees (D. Smith, Dyson, Jabbari), engaging with medicine and plant biotechnology. The UoA commenced targeted expansion in line with REF2014 goals: Montenegro-Johnson (from Cambridge) specialises in continuum mechanics for biological and bio-inspired systems, Spill (MIT) in stochastic modelling and cancer mechanobiology, and Johnson (Warwick) in networks and complex systems. These posts complemented and broadened the theme's activities, leading to a Leverhulme Research Leadership Award (Montenegro-Johnson) and a UKRI FLF (Spill), alongside other awards. Smith's software FAST (Flagellar Analysis and Sperm Tracking) is undergoing trials for couples undergoing IVF at Birmingham Women's Hospital and has attracted interest from eight international clinics.

The UoA plays a central role in SMQB (Sec.3.2), recruiting Terry in 2019, and an associated group of externally funded fellows focusing on dynamical systems analysis applied to epilepsy and neuroendocrine disease. Recent successes include Woldman's Epilepsy Research UK

Emerging Leader Fellowship, and a Medilink UK National Startup Award to translational spin-out Neuronostics. Part-time Chair Viktor Jirsa (INS Marseille and leader of the international Virtual Brain Project) brings further translational expertise.

2021-26 Objectives: To apply modelling to data science and machine learning, focusing on mathematical neuroscience, endocrinology, microbiology and mechanobiology; to capitalise on integration with other core strengths, particularly in applications of 'pure' graph theory to network science for health, and optimisation to infer neurological connectivity and processes underlying normal and dysfunctional brain activity.

Algebra

Algebra has evolved to encompass world-class research in representation and Lie theory alongside established strengths in group theory and its generalisations. Craven and Goodwin lead representation theory, focussing on algebraic groups, Lie algebras and finite groups of Lie type. Topley (post-census, UKRI FLF) brings expertise in Lie theory and Poisson geometry. Core activity in group theory includes major outputs by Craven, Flavell, Goodwin, Magaard, Parker and Shpectorov. The latter's influence has drawn significant international interest in axial algebras, evidenced by e.g., his Heilbronn Focused Research Workshop (Bristol 2018; further workshop planned for 2021/22). Another highlight is Craven's determination of the maximal subgroups of certain exceptional groups, providing the first progress on the complete classification of such subgroups for all prime powers since Malle's highly cited work (1991).

2021-26 Objectives: To create major impact in modular representation theory of Lie algebras. To build on this global research programme to understand subgroup structure of finite simple groups; develop research on local-global conjectures in group representation theory; continue to lead on finite simple groups and their classification.

Analysis

Since 2014, Analysis has consolidated its position as an international centre for harmonic analysis and its interactions. With early-career appointments Martini, Morris (Oxford), Oliveira e Silva and Y. Wang, it is rapidly becoming an international destination of choice for postdoctoral fellows and international visitors. Eleven were supported during this cycle, via e.g., Bennett's ERC Grant and several visiting fellowships (Marie Skłodowska-Curie, Japan Society for the Promotion of Science, POSCO Korea).

The theme has broadened its activity into stochastic analysis through JBJI appointments Duong (Imperial) and Huang. Key theoretical advances include proving the nonlinear Brascamp-Lieb inequality (Bennett, *Duke* 2020) and a major breakthrough in the control of fractional Riesz transforms (Reguera, *Memoirs AMS* 2020).

2021-26 Objectives: To lead on emerging themes in (i) geometric aspects of real and harmonic analysis, particularly in the control of oscillatory and singular integrals, PDEs and geometric measure theory, and (ii) probabilistic and variational approaches to nonlinear dispersive, kinetic and diffusion equations.

Geometry and Mathematical Physics

Mazzocco (recruited in 2018, as theme lead), establishes activity across integrable systems, the Langlands programme, algebraic and enumerative geometry, and mathematical physics. Recent work has produced a representation theoretic approach to the theory of the Painlevé equations and, with Chekhov and Rubtsov, a step towards the ambitious goal of describing all Gross-Hacking and Keel theta functions in the non-commutative world (*Adv. Math* 2020).

Kelly (from Cambridge, UKRI FLF 2020) catalyses activity in algebraic geometry. Working in mirror symmetry, he has proved three conjectures about derived categories that arise naturally in Kontsevich's homological mirror symmetry conjecture (*Am. J. Math* 2017).

Van Garrel (post-cycle, Warwick) strengthens connections with enumerative geometry. Peón-Nieto, known for her proofs of conjectures by Donagi-Pantev (as part of the Langlands programme), joins post-cycle following a Marie Skłodowska-Curie Fellowship. Closset (post-cycle, Oxford; RS URF) has attracted significant attention in high-energy physics.

2021-26 Objectives: To establish a leading centre encompassing geometry and quantum field theory, hosting a Programme Grant Hub. Synergies in integrability, mirror symmetry and geometry will impact algebraic geometry and string theory, including new Landau-Ginzburg enumerative techniques, applications to Donaldson-Thomas theory, super-conformal field theory, Langlands programme and generalisations of the topological recursion technique.

Nonlinear Systems and Continuum Mechanics

The UoA has long-standing strengths in free surface hydrodynamics, including two EPSRC projects with industry (Shikhmurzaev, with Schlumberger Gould Research and Tata Steel). Shikhmurzaev's contribution to a Programme Grant in Nottingham implements his internationally recognised Interface Formation Model, described in his landmark monograph *Capillary Flows with Forming Interfaces* (250 citations). Q. Wang holds joint funding with Dentistry to improve ultrasonic dental appliance cleaning through bubble dynamics.

2021-26 Objectives: Build on recognised strengths in free surface fluid dynamics and interfacial flows in strategically important areas. Grow links with EPSRC CDT in Formulation Engineering, and healthcare technologies, e.g., liquid jet and bubble dynamics applied to drug delivery.

Optimisation, Numerical Analysis and Statistics

This theme unites expertise in large-scale optimisation, optimisation in data science, numerical linear algebra and tropical mathematics, uncertainty quantification, and applications in healthcare, epidemiology, ecology and finance. Major activities include hosting the biennial IMA Conference on Numerical Linear Algebra and Optimisation (since 2007), Kocvara's research in conic optimisation and associated applications (Sec.1.1 and PENCOR **Impact Case Study**) and participation in the Horizon 2020 POEMA Network, and Bespalov's contributions to the T-IFISS toolbox for adaptive finite elements for uncertainty quantification.

This theme underpins excellence in other areas, e.g., Petrovskaya's contribution to Shikhmurzaev's EPSRC-funded research on oil recovery, and Loghin & Tzella's recent advances beyond homogenisation theory to capture dispersion with non-Gaussian tails (*Proc R. Soc A* 2020). New appointee Sergeev maintains activity in tropical mathematics following Butkovic's retirement, strengthened by the appointment of Jones, and growing interaction with railways and robotics. J. Li introduces new activity in optimisation for data science, bringing expertise in medical image analysis. Bespalov and Loghin apply uncertainty quantification and PDEs to deep learning in scientific computing, supported by Bespalov's Turing Fellowship.

In statistics, Chakraborty develops robust multivariate methods and applications in respiratory medicine with Birmingham Heartlands Hospital, and Hemming (UoA2) leads stepped-wedge trial design for health interventions, contributing to a UoA10 **Impact Case Study**. Early-career appointments in numerics for stochastic differential equations (Shang, ETH) and epidemiology (Touloupou, Warwick, post cycle) further broadens the theme's activities and strengthens data science.

2021-26 Objectives: To develop theoretical underpinnings of deep learning for scientific computing; strengthen the clinical and healthcare interfaces, particularly in epidemiology and medical image analysis; capitalise on institutional strengths (Birmingham Health Partners, 2.1.3-REF5a; Health Innovation Campus, 4.2.2-REF5a; Rail 4.2.3-REF5a; Interdisciplinary Data Sciences, 2.4-REF5a).

Topology and Dynamical Systems

Following significant theoretical achievements, e.g. on shadowing in Dynamical Systems (*Inventiones* 2020), and after hosting externally funded fellowships (4 this cycle, including a Marie Skłodowska-Curie Fellow), this area has expanded considerably, with three new appointments. Baker (Warwick) works at the interface of dynamical systems and number theory (e.g. *Adv. Math.* 2020 and 2021), Kombrink's research is in geometry and stochastics and Samuel works primarily in fractal geometry.

2021-26 Objectives: To grow this relatively young theme through continued postdoctoral appointments; to develop intradisciplinary research in aperiodic order, iterated function systems, beta maps and shadowing and their relationships to quasicrystals, number theory, probability theory and stability theory.

1.4. Progress towards an open research environment

The UoA is fully committed to Open Research, maximising engagement and impact through open access publications, code, and editorial contributions to open access journals.

The University's Open Research Group (2.2-REF5a), emphasising DORA and Plan S, guides UoA-level activities ensuring the use of fair and responsible metrics in research and staff assessment (probation and promotion) and actively promotes open publication. The University's Advanced Research Computing team provide monthly Research Data Drop-ins and the Library provides a VLE course on Research Data Management.

In addition to uploading author-accepted manuscripts to the University's repository UBIRA (over 400 between 2014-20) and arXiv (529 between 2014-20), we increasingly publish papers (over 170 between 2014-20) in gold or diamond open access journals; the former is supported by University UKRI and COAF funds. The UoA provides leadership in the development of open access journals (e.g., Kühn's editorship of *Advances in Combinatorics*; Sec.4.4).

A recent initiative to enhance open research is the appointment of Open Research Champion Gallagher to develop a webpage curating publications, code and data. This builds on successes such as Kocvara's PENLAB optimisation software, with over 1900 downloads worldwide. Researchers benefit from training and contract engagements by Research Software Engineering (4.5-REF5a) to develop reusable/shareable code.

1.5 Research Integrity

The University's Research Governance Ethics and Integrity Committee and annual Statement on Research Integrity (2.2-REF5a) supports the UoA on research-related ethical issues. Following the Concordat to Support Research Integrity, the Director of Research is responsible for relevant training. All PGRs and staff receive training on Research Integrity in Mathematics, including plagiarism, presentation of research methods and procedures, fair presentation of results, guidance on joint authorship, acknowledging the work of others, availability of code and data for reproducibility, and making fair and justifiable claims. All staff undertake compulsory biennial Data Protection training.

1.6 Sustainability: Five year vision and key future aims

The UoA enters the next cycle with a vibrant cohort of early-career staff holding significant external funding, greatly strengthened senior leadership in pure and applied mathematics, a new strategic centre in SMQB, and growing engagement with healthcare and industry. Building on this success, our vision is to broaden existing areas of excellence and grow to become recognised as world-leading across a broad range of research themes, and

associated societal impact.

UoA-level actions to deliver 2021-26 aims:

- **Sustainable growth** to 70 permanent FTE over the next 5 years, leveraging transnational activity such as JBJI, enabling expansion in key scientific areas (outlined below).
- **Knowledge exchange and impact.** Increase engagement with the national KE agenda, exploiting Dyson's membership of the Newton Gateway Scientific Advisory Panel. Strengthen the UoA's industrial engagement, building on established activity in Optimisation, Statistics and Continuum Mechanics, and build engagement in other areas of strength including Discrete Mathematics. Utilise horizon scanning to identify emerging societal needs for mathematics. Through these mechanisms, enhance the breadth and depth of the UoA's impact.
- **Interdisciplinarity**, with particular focus on Data Science and Statistics expansion: capitalise on strategic investment in SMQB and NHS partnerships, growing activity around new appointments in Computational Statistics (J. Li, Shang) and Epidemiology (Touloupou), and increase engagement with the Turing Institute, particularly in network science and uncertainty quantification (Bespalov, Fountoulakis, Johnson).
- **Investment.** Support institutional strategy (2.1.4-REF5a), by growing grant capture to ensure a 50% increase in PDRA numbers, thereby enabling fundamental and impactful research and cementing Birmingham as a destination of choice for early-career researchers.
- **Connectivity.** Continue the programme of strengthening and diversifying Pure Mathematics including in areas that connect theoretical and impactful research (e.g., combinatorics and network science, probability and data science).

2. People

2.1. Staff development strategy

As a UoA that has significantly expanded particularly through investment in early-career researchers, we place great emphasis in providing an inclusive, flexible training and developmental environment within which equality, diversity and inclusion (ED&I) is embedded. This environment, shaped by the Vitae Concordat, which provides 'opportunities, structured support, encouragement and time for researchers to engage in a minimum of 10 days professional development pro rata per year', enables individuals to realise their career ambitions whilst collectively contributing to our wider research and impact objectives.

Training and development for all staff

The annual Performance and Development Review (PDR) enables staff to reflect upon career aspirations, identify development needs for their research careers, and mechanisms to support progression, including training, mentoring/coaching, study leave and access to internal funds, along with balancing duties to ensure sufficient time is available for research.

All new staff undertake a University induction coupled with a bespoke UoA-level induction that includes compulsory training in key areas including ED&I, and are assigned a mentor from within the UoA to enhance their transition.

Training and mentoring activities include institutional provision (3.4.2 and 3.4.4, REF5a), College-level grant writing workshops (14 attendees), programme-specific workshops (e.g., EPSRC New Investigator Awards and Fellowships), coaching and mock interviews. Tailored workshops and development days have focused on funding applications, industry

engagement and ED&I.

Leadership development

A specific objective has been to strengthen leadership amongst existing staff to improve resilience and aid succession planning through:

- **Training:** Since REF2014 five UoA staff (Good, Leppinen, Meyer, Montenegro-Johnson, D. Smith) have completed/recently commenced, University-level *Senior, Emerging and Research Leadership Programmes* delivered by *People and Organisation Development*.
- **Support** to enhance senior leadership roles, e.g., through the provision of advance study leave (e.g., Good – Head of School).
- **Strategic recruitment** expanding research leadership in key themes (Sec.1.3).
- **Mentoring and coaching:** newly created roles facilitate the transfer of expertise and develop research leadership skills, e.g., Interdisciplinary Research Officer (Spill), Knowledge Exchange Lead (Montenegro-Johnson), and Early-Career Fellowship lead (Montgomery).

Four UoA professors (Kühn and Osthus, recruited in 2004 to establish Combinatorics; Bennett, recruited in 2005 to establish Analysis; D. Smith, recruited in 2009 and now co-leading Mathematical Biology and Healthcare) were initially early-career appointees, demonstrating the success of our strategy. Four recent promotions to Reader (Dyson, Fountoulakis, Goodwin, Maleva) are being supported in a similar way, as are more recent appointments to Birmingham Fellowships (Carmesin, Craven, Jabbari, Lo, Montgomery, Reguera, Treglown) and Lectureships (Kelly, establishing the Algebraic Geometry sub-area; Montenegro-Johnson, linking with Chemical Engineering; Spill, establishing mechanical systems biology).

2.2. Staffing and recruitment policy

Overseen by UoA Executive, our staffing and recruitment policy is driven by the desire to grow sustainably while maintaining a diverse, vibrant and collegial environment. Beyond supporting the development of existing staff, we have ambitiously expanded, achieving critical mass in a number of themes (Sec.1.3). Our strategy of recruiting early-career appointments at REF2014 has broadened to include developing senior leadership through recruitment and internal promotion with an emphasis on ED&I (Secs.2.5, 2.7).

Annually, and in conjunction with the lead(s) of each theme, the Executive reviews its five-year recruitment plan. Priority areas are identified, to encompass current and emerging research trends within each theme, opportunities for translational research and knowledge exchange, alignment with the UoA's internationalisation and ED&I strategy. For each new role, a recruitment strategy is developed to ensure the very best current and emerging researchers are identified. A senior academic is identified to lead recruitment for each role, with strategic oversight provided by the Executive, to ensure UoA-level priorities, for example ED&I, are realised throughout the recruitment cycle.

Through this approach, 28.2 new Category A FTEs (c. 50% growth) were appointed this cycle, including 3.2 at Chair. Terry brings translational research on epilepsy diagnosis and prognosis (including through the award-winning spin-out Neuronostics); along with fractional appointee Jirsa, this complements existing strengths in Mathematical Biology and Healthcare. The appointment of J. Li catalyses expansion of impact in Data Science (Sec.1.6). Mazzocco's new theme in Geometry and Mathematical Physics enables further interaction outside of mathematics.

With over 25 early-career appointments, there has been significant investment to strengthen

existing themes and invest in new areas of Topology and Dynamical Systems, and Geometry and Mathematical Physics. Recruiting established leaders and outstanding early-career researchers, coupled with internal promotions (Sec.2.5) and our policy to appoint on permanent contracts (all but two Category A staff are permanent), ensures sustainability in leadership.

Diversity is an important focus. We have:

- Maintained a balance of senior, mid- and early-career staff, facilitating succession planning. At census date, 31% of staff were Readers/Professors compared with 32.5% in 2013, despite the increase in FTE.
- Improved the number of female senior academics (50% of Readers and 14% of Professors, double national average).

Our 2021-2026 objectives are to:

1. Sustainably grow to 70 permanent FTE (Sec.1.6).
2. Further increase staff diversity:
 - Increase the proportion of female/non-binary staff to above the national average in mathematics.
 - Consistently obtain at least a quarter of female/non-binary applications for permanent positions.
3. Build on successes in supporting fellowship applications and encourage/support staff to secure large grants (Sec.3.1).

We monitor diversity statistics throughout recruitment, taking positive action, if necessary, to mitigate unconscious bias. Guided by recommendations from Learned Societies (e.g. *LMS Good Practice Scheme*), our ED&I Committee reviews our external profile and internal processes to ensure we recruit from a maximally diverse talent pool. Kelly is a member of the LMS Women in Mathematics Committee, providing a link to national policy and practice.

2.3. Supporting Early-Career Academics/PDRAs

Lecturers/Fellows receive a relocation and start-up package (indicatively £5K), and support for visa applications. Newly appointed academic staff receive support during probation from the Director for Staffing (Dyson), and a mentor with whom they meet at least quarterly to review progress against agreed objectives and identify development opportunities. During probation, staff have a substantially reduced teaching load, supporting their research. Birmingham Fellows have five years' reduced teaching and administration. Newly recruited senior staff are afforded at least a year of reduced administration and teaching. Probationers are prioritised for PhD scholarships and supported by experienced co-supervisors. In this cycle, almost all probationary staff supervised PGRs.

Postdoctoral Research Associates are supported by an annual Performance Development Review (PDR, Sec.2.1) and have a plethora of training opportunities available. The College's *Postdoctoral and Early Career Development and Training* scheme organises thematic training sessions (PDRA Luo is an active committee member), including *Open Research, Engagement Outside Academia*, and *Research Grants - Where do I Start?*

Ten PDRAs have taken the opportunity to teach advanced undergraduate modules and are able to develop supervision/project management skills by supervising master's projects with the close support of an experienced co-supervisor. For example, Neal's MSci project with PDRA Gallagher on model-based image analysis resulted in a publication (*Interface* 2017). PDRAs contribute to decision making and help shape policies, support and training

provision, through membership of ED&I, Research and Athena Swan committees.

85.7% of PDRAs (surveyed 2020) were very satisfied with the 'quality of guidance and mentoring' received. Over fifteen PDRAs who joined this cycle have already moved to permanent academic positions, e.g., at Charles University, Heidelberg, KAIST, Kent, Ryerson, Umea, UPC Barcelona, and Warwick. PDRAs have also secured scientific roles in industry e.g., at Huawei, NevaLabsHQ and Sony.

2.4. Study/impact leave and staff exchange

All post-probation staff can apply for a semester of **study/impact leave** every three years, ensuring academics at every career stage have periods of intense research focus, supporting impact generation (Sec.1.2) and international collaborations. This cycle, 23 staff took at least one period of leave. Researchers used this time to visit MSRI Berkeley (Maleva), INI Cambridge (Bespalov) and UIUC (Treglown), explore new industrial partnerships with Ironclad Biosciences (Jabbari) and Phytoponics (Dyson), prepare grant proposals (D. Smith's Healthcare Technologies Challenge Award) and write monographs (Parker).

Staff exchange is facilitated through the themes with oversight maintained by D. Smith (Director of Research), with expertise in brokering and developing relationships provided by Montenegro-Johnson (Knowledge Exchange Lead). This flexible and supportive approach allows emerging opportunities for collaboration with industry to be efficiently realised. For example, a number of PhD projects have involved industry placements (e.g., PGR Thomson with P&G, and PGR Cupples with Linear Diagnostics Ltd). Examples of sustained relationships established through movement of staff and PGRs to industry include former Category A staff Otto (R&A, underpinning an **Impact Case Study**), and PGRs Fiala and Schlueter (underpinning translation of PENLAB and the MIDACO **Impact Case Study**).

2.5. Recognition/Reward

We proactively support and encourage promotion applications and nominate staff for awards and prizes; successes include Kuhn's Wolfson Merit Award and Montgomery's Philip Leverhulme Prize.

The Promotions Committee systematically reviews all staff annually to avoid unconscious bias and to identify individual career development needs against University promotion criteria. Every staff member seeking to apply for promotion is provided with an experienced mentor, with additional feedback provided by the UoA's Promotion Committee, and interview practice. Unsuccessful applicants debrief with a senior colleague to review their feedback and identify future development needs.

This cycle 6 female and 16 male Category A staff have been promoted, with 2 female, 2 male promoted twice. There have been 19 promotions to Senior Lecturer, 4 to Reader and 3 to Chair. The success rate was 72%.

2.6 Research students

PhD awards have risen to an average of almost 13 p.a. this cycle (20% increase). Over the past three years, 42% of PhD graduates were from overseas; 20% of graduates were female/non-binary, the latter motivating an Athena Swan Bronze objective to exceed the national benchmark of 26% (LMS Benchmarking Study 2017). PGR expansion has resulted from increased grant-supported studentships, increased EPSRC DTP scholarships due to growth in our funding portfolio, strategic internal investment, and our growing reputation as

a destination for outstanding graduates. 41 PGRs commenced **UKRI-supported studentships** this cycle, with many studentships being part-funded by the institution. We aim to maintain this rate of growth in the next cycle (19 PGRs commenced studies in 2020).

The volume and quality of PGR research continues to grow, e.g., Whitley resolved the 25-year-old Dipper-Du Conjecture (*Proceedings LMS*, 2019). In “The existence of designs via iterative absorption” (*Memoirs AMS*, to appear), Glock and co-authors Kühn, Lo and Osthus proved a wide generalisation of the Existence of Designs Conjecture; the cornerstone question in Design Theory, this conjecture from 1853 had only recently been solved by Keevash. Glock received the 2018 Richard Rado prize for his PhD thesis. Beltran was awarded the Vicent Caselles prize from the Real Sociedad Matematica Espanola for contributions to harmonic analysis.

Graduates have secured research or permanent positions in academia, e.g., at Bilbao, Bristol, Czech Academy of Sciences, ETH Zurich, Oxford, Sao Paulo, Zagreb, and in industrial science and engineering, e.g., Arup, Bosch, Fiecon, Tessella.

Approach to recruiting doctoral research students

The UoA’s vision is to attract outstanding graduates, irrespective of protected characteristics, and encourage and enable progression into research careers.

We work with all undergraduates to promote research-related careers and foster their mathematical confidence. For example, promising Year 2 students are encouraged to transfer to the MSci. Masters’ dissertations and LMS/EP SRC/BBSRC summer projects (e.g., 7 LMS bursaries 2015-19) have proved an effective bridge to PhD research, often yielding publications e.g. Kerr and Thomson (*Roy. Soc. Open Sci.*, 2019), Bowtell (*Graphs and Combinatorics*, 2020), Dari (*J. Biomechanics*, 2019), and three papers arising from Thomas’s project, working with Good. Several such students have subsequently entered postgraduate research in Birmingham and elsewhere (e.g., Oxford, Manchester, Nottingham). For example, seven (4 male, 3 female or non-binary) of the fourteen PhD/MRes students that started in the UoA during 2018/19 were Birmingham undergraduates.

To encourage engagement with these opportunities and to stimulate interest in further study, internal mentoring and PGR prospects events are held throughout the year, with a focus on underrepresented groups. These activities have been complemented by rewriting the UoA’s externally-facing webpages to emphasise our inclusive culture, and ensuring that admissions events (e.g., open days, applicant visits to research groups) are supported by a diverse sample of the current postgraduate community.

Building on current approaches, goals for the next 5 years are to:

- Continue to review and enhance postgraduate admissions, encompassing all activities related to external recruitment of postgraduate researchers (advertising, webpages, interviews).
- Internally core fund 5-10 additional summer placements each year.
- Improve the gender balance of internal PhD scholarship applicants through continued targeted mentoring.

Training environment and student development

Student-supervisor relationships are very strong, with weekly meetings of at least an hour and collaborations often continuing for years beyond graduation. Regular reading groups and seminars help integrate PGRs into our research culture. There are eight (weekly) term-time seminar series and twice-termly Mathematics Colloquia. Reading groups provide PGRs (and PDRAs) opportunities to engage collectively with contemporary research topics over a sustained period and a supportive atmosphere for delivering presentations. PGRs

benefit from the UoA's participation in four LMS Scheme 3 Networks (in Algebra, Analysis and Topology), through which they present work to their broader community.

The UoA belongs to the 21-strong Mathematics Access Grid Instruction and Collaboration consortium; videoconferencing technology provides access to broad and deep mathematical training (35 different courses available in 2018/19). PGRs undertake at least five such courses during their degree (at least 100 hours of training). PGRs also have the opportunity to undertake limited, but supported, teaching tailored to their experience to enhance career development. Further UoA activities support PhD students, including the round-the-table discussion "How to apply for a postdoc".

The postgraduate researcher hub, Westmere (3.2-REF5a), provides interdisciplinary development events and leadership opportunities, e.g., via the Westmere Scholarship (held by PGR Chloe Spalding). Other support is provided by the Careers Network and the University's Writing School.

PGR integration into the academic community

PGRs are supported and mentored to gain experience organising conferences. The UoA has hosted the British Early Career Mathematicians' Colloquium (formerly BYMC) five times since 2015, and in 2014 and 2019, hosted the Postgraduate Group Theory Conference. All PGRs receive travel funds, typically enabling participation in several (inter)national conferences and summer schools. Other internal training activities include an annual research poster presentation event.

International research links for PGRs are developed through several initiatives: engagements with the Universities of Auckland and Melbourne via the Universitas 21 collaboration and knowledge exchange network; ERASMUS exchanges with Umea, Sweden; joint-site PhD programmes with Adelaide and Nottingham. The UoA-led Multiscale Biology Study Groups (2016, 2017; supported by BBSRC, EPSRC and the Institute of Advanced Study, 2.3.1-REF5a), enabled 40 participants, mostly PGR/PDRA, to collaborate with international visitors, leading to publications and interdisciplinary exposure.

We contribute to Doctoral Training Programmes across other disciplines, e.g., rotation projects in the Wellcome Trust Mechanisms of Inflammatory Disease (MIDAS) DTP. Co-supervision with Leverhulme/Birmingham Institute for Forestry Research, EPSRC Doctoral Training Centres in Birmingham (SciPhy4Health, TopDesign) and Warwick (MathSys/MOAC), and Bubble Dynamics (Jiangsu University of Science and Technology, China) provide interdisciplinary training for both Birmingham and external students.

PGR monitoring and support

In addition to weekly meetings, postgraduates have monthly structured reviews with their supervisors. Progression is assessed through first-year reports, followed by a second-year dissertation. Co-supervisors provide additional academic support and development advice. Mentors provide support with issues that may affect their studies. Welfare Officers provide specialist pastoral support to PGRs.

Students have been supported with up to 3 months paid sick leave and, in 2020, eight students whose studies were disrupted by the Covid-19 pandemic were awarded 1–3-month funding extensions. **Since 2013, all but three PGRs have successfully completed.**

2.7. Equality, Diversity and Inclusion

The ED&I Committee includes gender and ethnicity-balanced representation, and members at every level from undergraduate to professor. The Director of ED&I is on the Executive; all members of the Executive are active Committee members. The UoA recently renewed its

Athena SWAN Bronze accreditation (2018-22) and is pursuing an action plan to enhance ED&I.

Ensuring equality of opportunity and outcomes

PDR (Sec.2.1) forms the basis for developmental discussions. Teaching duties are typically limited to 50-75 lecture hours for research-active staff, with reduced loads for new starters and those returning from parental/adoption leave. Further reductions are made for staff holding substantial funding. Similarly the Promotions Committee supports recognition of success (Sec.2.5).

Panels assessing applications for internal funds, training/leadership opportunities, and studentships are gender-balanced and all members undergo ED&I training. These measures support success in obtaining external funding regardless of protected characteristics (Sec.1.2).

Ten of the (census date) Category A staff are female, with several recent promotions (Sec.2.5). In 2018, we appointed our second female professor, Mazzocco, who led Loughborough to an Athena SWAN Silver Award, and is a strong advocate for diversity at UoA and (via the Senate) Institutional levels. A key goal is to develop best practice in support of a Silver application by September 2022.

In the construction of the REF submission, output reviews were undertaken by a broad cross-section of staff across all research groups, each output being read by at least two reviewers. In accordance with the University's REF Code of Practice, and to ensure equity, equality and transparency, Output Selection Group members (comprising four senior staff, including one female) received compulsory ED&I training and compared the pool of available outputs with the outputs selected for submission for consistency and fair representation. Internal scoring was monitored for potential biases and to ensure that particular output types or research areas were not promoted over others. 15.2% of submitted outputs are attributed to members of staff identifying as BAME, 17.4% as female; 19.3% of submitted staff identify as BAME, 17.5% as female.

Promoting diversity

The School has a culture of bringing mathematicians of all levels, from undergraduate to staff members, together in an inclusive community. Since 2018, the UoA has hosted Women in Mathematics events for female and non-binary staff and students to informally discuss experiences, career development and barriers to progression. Similar events for BAME staff and students are held on regular basis; Jabbari is academic contact for the BAME science students' society. We organise a range of informal student engagement events each term, e.g., *Mathematical Musings* discussions over coffee.

We are proud to be part of an institution recognised by Stonewall in 2017 as one of the UK's Top 100 employers for LGBT+ staff. Kelly organised the 2020 LGBT+ STEMinar Conference (c. 275 participants). The series showcases the diversity of STEM academics and provides role models for LGBT+ scientists who are either at a junior stage in their careers or are considering the possibility of going into a STEM field. The conference was supported financially by the UoA alongside 13 external sponsors (including the RS, LMS and IMA).

Before staff take **parental/adoption leave** they discuss with the Head of School preferences around flexible working, and duties on return from work. Going beyond University-wide policies, a term of study leave is provided following return from maternity and significant parental/adoption leave, followed by an additional term of reduced administration and teaching. Whilst staff are on leave, keeping-in-touch days provide an opportunity to remain engaged in the research environment. Staff returning from leave are not asked to teach new modules. Institutional support can be requested to help restart

research, e.g., to support a collaborator's visit. To assist with return to work, staff have made use of institutional financial support, e.g., funds to support a collaborator's visit to Birmingham (to minimise travel).

Recognising the range of personal circumstances that staff may encounter, and the range of working styles that mathematicians find effective, *all* staff who have worked at the University continuously for 26 weeks may make a **flexible working** request. This measure aims to support staff to organise their research activity in a way that is optimal for them. In the 2018 staff survey, only 1 out of 44 respondents disagreed with the statement 'My line manager/supervisor is supportive of requests for flexible working'. The UoA has a policy of only organising meetings during core hours.

ED&I training events are run by both the UoA and Institution. For example, in February 2019, staff engaged in an unconscious bias workshop as part of a UoA away day. All staff are required to have completed a Diversity in the Workplace online module and to undergo Unconscious Bias training, thereby enabling recruitment of the best researchers.

For colleagues with **disabilities or health** issues, reasonable adjustments are made including agreed scheduling of academic activities. Resting rooms are provided for staff with health requirements at off-site development events.

Best practice examples

- The UoA was the first in the University to provide gender-neutral toilets in 2017.
- Since 2013, weekly term-time coffee mornings have been organised by staff volunteers and widely attended by staff and PDRAs. This initiative was highlighted by the LMS Good Practice Scheme (Ortus Economic, April 2018).

3. Income, infrastructure and facilities

3.1 Research funding and strategies for generating research income

Mechanisms to support funding applications

Support for grant applications is led by senior academics in each theme, working with the Grants Director (Osthus) and Director of Research (D. Smith), alongside the Research Support Office (Sec.3.3); activities include peer review, sharing examples of successful applications, mock interviews, executive coaching, informal 'drop in' sessions with senior staff, and the College's Grants Development Series, a twice-yearly programme of workshops tailored to individuals. Staff development days include training on grant drafting and peer review exercises. We have hosted EPSRC representatives to discuss strategy for the mathematical sciences. The UoA provides financial support for proposal development, including travel and visitor costs, in addition to PGR scholarship match funding and reductions in teaching commitments.

The University's European and International Research Support team provides expert support for applications to international funders. Recent successes include Kocvara's EC Innovative Training Network for the "POEMA" project, Kühn's ERC Advanced Grant, ERC Starting Grants (Bennett, Kühn, Montgomery, Osthus) and several Marie Skłodowska-Curie Fellowships. Study leave, internal funding schemes (Sec.4.1), applied and interdisciplinary areas, industry interaction, research visits and secondments all provide proven catalysts for competitive external grant applications.

Income strategy and outcomes

The UoA's staffing strategy to recruit outstanding early-career academics has enabled a focus on competitive fellowship and new investigator awards from UK and EU research councils (Table 1). This accounts for much of the success in this cycle (208% increase in UK research council income and a 313% increase in EU income; moving the UoA from rank 22nd in the Russell Group for research council income per FTE in 2014-15 to rank 11th in 2018-19 – HESA). Several early-career appointees have already secured support extending into the next cycle: Carmesin's £1M EPSRC Fellowship (until 2025); Kelly's £1.3M UKRI FLF (until 2024); Montgomery's €1.4M ERC Starting Grant (until 2025); Spill's £1.3M UKRI FLF (until 2024). Senior staff also have significant ongoing funding: Kühn's €1.8M ERC Advanced Grant (until 2023); Terry's post-census £1.9M EPSRC Fellowship (until 2026).

In addition, 8 PDRAs were supported by national and international funding not included in the UoA's research income figures (e.g., Deutsche Forschungsgemeinschaft, Swiss National Science Foundation, Japan Society for the Promotion of Science).

HESA Funder Type	Research Income REF2014	Research Income REF2021	Percentage increase	Number of staff funded (REF 2021)	Number of research themes funded (REF 2021)
UK research councils	£2,345,105	£7,218,715	208%	36	7
<i>BBSRC</i>		£388,385		2	1
<i>British Academy</i>		£2,288		1	1
<i>EPSRC</i>		£5,905,161		32	7
<i>MRC</i>		£272,326		2	1
<i>RS</i>		£650,555		3	3
EU Government bodies	£625,996	£2,587,810	313%	10	6
Other	£350,309	£385,664	10%		
Total research income	£3,321,410	£10,192,189	207%		

Table 1: Research income by funder type (REF2014 and REF2021 assessment periods)

Future income strategy**1. Increase support at postdoctoral level**

While Early-Career Fellowships have proved a major area of success for the UoA, the increased number of PDRAs and PGRs motivates greater support for postdoctoral fellowships, enabling the transition to research independence. Montgomery was recently appointed as Early-Career Fellowship lead, organising workshops and generating resources for sharing successful practice across the UoA. We will further develop our successful mechanisms to support New Investigator and Standard Grant awards.

2. Grow both blue skies and translational research through diversified income sources from industry, charity and healthcare

Recent progress in diversifying income sources for blue skies research includes Montenegro-Johnson's Leverhulme Research Leadership Award (£1M, until 2025) and

Montgomery's Philip Leverhulme Prize (£100K, until 2024).

Translating mathematical research into clinical and industrial outcomes requires significant additional external support. Recent success includes Woldman's Epilepsy Research UK Fellowship (£299K, to 2024) and NIHR Phase 1 and 2 awards (2020) to further grow spin-out Neuronostics (not included in income figures). Existing collaborations (e.g., University Hospitals Birmingham, Numerical Algorithms Group) together with new expertise in Healthcare (Terry, Neuronostics) and Data Science (J. Li) provide the basis to further increase engagement with industry, charity and healthcare.

3. Build on strategic appointments to compete for Centre and Programme Grant funding

The recent appointment of leaders such as Mazzocco and Terry, with concentrated funding already in their research areas and a track record of leading major initiatives (e.g., Terry's EPSRC Centre for Predictive Modelling in Healthcare, 2016-21), provides the capability to compete for further large-scale strategic investments.

3.2 Organisational infrastructure supporting research and impact

Staff and students undertaking interdisciplinary research benefit from a campus university, and nearby University Hospital, Women's Hospital and Dental School, the geography of which enables seamless working. Jabbari and D. Smith supervise researchers undertaking experimental work in the Birmingham Women's Fertility Centre & Centre for Human Reproductive Science, School of Biosciences, Institute of Immunology and Immunotherapy, and Institute of Inflammation and Ageing. D. Smith's development of the FAST software for diagnosis of male factor infertility was enabled through interaction with the Birmingham Women's Fertility Centre (EPSRC Healthcare Technologies funding), where it is being clinically assessed with couples undergoing IVF.

Institutional infrastructure (4.2.3-REF5a) supports UoA research and collaboration through shared laboratory and office space. Facilities include the Centre for Human Brain Health (Terry, Jirsa and Woldman's epilepsy research, plus interactions across Mathematical Biology and Combinatorics), BiFoR Free Air Carbon Enrichment (Dyson's research on plant root growth, Petrovskaya's work on pest spread in forests) and the Healthcare Technologies Institute (Spill's systems mechanobiology experiments; Montenegro-Johnson's 3D bioprinting research).

Our Turing Fellows regularly use the Turing Institute's facilities for interdisciplinary collaborations. Johnson's collaborations with ATI-based researchers resulted in seven publications on resilient rail networks, networks shaping cooperation and conflict, and economic stability. Johnson's PhD student Mosquera spent two years at the Institute. Bespalov's fellowship stimulated new research in Machine Learning, Data Science and AI, resulting in a PGR project and a job in industry, along with workshops and University policy development in these areas.

SMQB provides a key mechanism to support interdisciplinary and translational research across mathematics and medicine. SMQB hosts 4 externally funded fellowship holders and 3 core-funded centre fellows who combine their projects with seed-corn incubator awards. The latter is a competitive scheme providing 6 months' 0.5FTE fellow support, assistance with public engagement, artist-in-residence, and industry engagement, in preparation for larger external funding bids and subsequent translation; the first projects commenced in 2020.

Further strategic development via the recruitment of Jirsa, Director of the Institut de Neurosciences des Systèmes, Marseilles, and lead for The Virtual Brain neuroinformatics

project, is building interdisciplinary links between the UoA and Birmingham's Centre for Human Brain Health.

Cross-departmental appointments bringing additional vitality to the UoA's interdisciplinary activity include Owen (0.25FTE Mathematics, 0.75FTE Immunology and Immunotherapy). His research is in single-molecule cell imaging and associated topological data analysis.

The University's Institute of Advanced Studies (IAS, 2.3.1-REF5a) provides support and facilities to tackle timely interdisciplinary challenges. Examples of engagement include D. Smith's, Model Parameterisation in Healthcare and Life Sciences: Extracting Knowledge from Data (2017), hosting IAS Fellows (Sec.4.1), and numerous invited talks at IAS workshops.

3.3 Operational and scholarly infrastructure supporting research and impact

Physical and Operational Infrastructure

Based in the Watson Building (£971K investment this cycle), the UoA is located at the heart of campus. All academic staff have single-occupancy offices providing dedicated space to meet PGRs and colleagues. The new £60M University library houses group study rooms available for research.

The Research Support Office (located within the Watson Building) provides assistance in grant proposal preparation, including drafting, internal peer review, training and mock panels. Impact development is supported by Research Planning, International Relations, the Public Engagement with Research team, UoB Enterprise, and the UoA's dedicated Outreach Officer.

Further to the School-wide Colloquium, each research theme has a budget to run regular seminars with external speakers, in addition to internal reading groups. Early-career researchers receive a research start-up (£5K) and the UoA has committed to establishing a travel fund for each member of staff to facilitate research development activity.

Computing

All staff and PGRs have free access to resources to support Advanced Research Computing through BEAR (Birmingham Environment for Academic Research, 4.5-REF5a). The *BlueBEAR* High Performance Computing facility has 3936-core, 1.3TB RAM Linux cluster with 100Gb EDR Infiniband interconnect. BEAR Cloud retains the power of traditional HPC but provides accessibility through a range of virtual machines. Following a 2019 investment in one of the largest IBM POWER9 AI clusters in the UK (10 servers each equipped with four NVIDIA Tesla V100 16GB Tensor Core GPUs and dual 18-core POWER9 processors; 3 servers for general access and 7 for any life sciences application). Kocvara's group utilised the power of BlueBEAR to solve high-dimensional nonlinear optimisation problems in the "Multi-level Methods in Constrained Optimisation" project (Fondation Mathématique Jaques Hadamard), underpinning the **Impact Case Study** PENCOR. BEAR enabled numerous outputs and interdisciplinary projects, including Q. Wang's bubble cloud models, D. Smith's analysis of sperm motility data with Birmingham Women's Hospital, Dyson and Smith's models of fibre-reinforced fluids, and Petrovskaya's computational modelling of pesticide usage.

From 2021, the University will host Baskerville, a £4M EPSRC Tier-2 regional HPC centre with 184 NVIDIA A100 Tensor Core GPUs. These facilities will provide an outstanding platform for data science and deep learning applications, in particular for the Optimisation, Statistics and Numerical Analysis group. Researchers also benefit from Birmingham's involvement with regional facilities, including Midlands Plus (2017-21) and the forthcoming Sulis ensemble computing facility (2020-24).

3.4 Benefits-in-kind

Collaborations with experimental groups, industry and the NHS provide substantial in-kind support. Q. Wang's collaborations with Jiangsu University of Science and Technology and Nanyang Technological University enable access to data on free surface flow problems. These data underpin at least 15 outputs, including Wang's highly cited 2015 *J. Fluid Mech.* paper describing the influence of buoyancy effects on bubble collapse. Shikhmurzaev secured experimental data valued at £800K from Schlumberger Gould Research. This contributed to a further £445K in EPSRC funding and will underpin research over the next 5 years. Montenegro-Johnson's experimental research on the mechanics of touch sensation and touch-virtual reality is supported by state-of-the-art haptic sensing equipment from Ultraleap and Actronika.

D. Smith benefits from data and staff time from the Centre for Human Reproductive Science, Birmingham Women's Hospital (with additional equipment from Hamilton-Thorne Inc.) and University Hospitals Birmingham. Jabbari's collaboration with University of Texas Southwestern Medical Centre generated data on antiadhesion molecule effects on bacterial infection, leading to two *PLoS Comp. Biol.* papers (2018, 2019). Dyson's collaboration with UCLA recently led to an extended joint-funded visit for a member of her team to generate data on plant cell growth. Kocvara's PENLAB software for linear and nonlinear semidefinite optimisation benefited from staff time for code development by the Numerical Algorithms Group Oxford, resulting in an official open-source NAG-sponsored product.

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

4.1 Research collaborations and supporting arrangements

Departmental and institutional awards (e.g., a College Travel Fund of £1000 p.a. per staff member) support international collaborations. Several competitive internally administered funds are also available to facilitate collaboration:

- *Wellcome Trust's Institutional Strategic Support Fund*: 35 (inter)national participants (from Mathematical Biology, Computer Science, Bioengineering, Statistics, Biosciences and industry) attended the workshop *Model Parameter Estimation for Predictive Medicine* organised by Jabbari. Five Birmingham-led interdisciplinary publications resulted (in *PLoS Comp Biol.*; *Interface*; *mBIO*; *Frontiers in Microbiology*), evidencing the benefits of reliable mathematical modelling in medicine, with applications to the current global challenge of tackling antimicrobial resistance.
- *Institute for Advanced Studies* (2.3.1-REF5a): Professor Gernot Stroth (Halle), a leading algebraist, acclaimed for his incisive contributions to the finite simple group classification, was supported to collaborate with Parker and colleagues in Algebra, leading to Parker and Stroth's monograph (submitted, *Memoirs AMS*).
- *BRIDGE Seed Fund*: Providing investment to grow the strategic partnership between Birmingham and UIUC (2.1.8-REF5a). This fund facilitated two-way visits in Combinatorics (Lo, Mycroft, Treglown). Treglown and co-authors Professors Jozsef Balogh and Alexandr Kostochka (UIUC) received funding for "Building Bridges in Mathematics", resulting in five major publications, including the resolution of a longstanding question of Cameron and Erdős at the interface of Combinatorics and Number theory (*JEMS* 2018) and underpinning Treglown's EPSRC Fellowship. In all, 10 publications have resulted from BRIDGE activities.

All themes have initiated wide-ranging and dynamic international collaborations, from

individual interactions to institutional joint ventures and multi-institution networks. Of the selected outputs, 75% involved collaboration with at least one other institution, 56% with an international collaborator, and 17% with another discipline. Below we give examples of collaborations in which staff have taken leading roles generating research ideas, funding proposals, and associated outputs.

A notable example in **Analysis** is the solution to the longstanding nonlinear Brascamp-Lieb problem (*Duke* 2020) in a collaboration with Bez (Saitama, Japan), Cowling (New South Wales), Bennett, and Birmingham PDRAs Buschenhenke (from Kiel) and Flock (from Berkeley). This work, funded by the ERC, JSPS and ARC, is the culmination of a decade-long Birmingham-led collaboration in multilinear harmonic analysis. Another highlight is the resolution of a twenty-five-year-old conjecture of Sarason by Reguera with Aleman and Pott, funded by a Marie Curie grant, joint with Lund University. Other examples of major collaborative projects involve Barcelona, Edinburgh, Missouri, Scuola Normale Superiore di Pisa, Seoul National University and Warwick.

In **Combinatorics, Probability and Algorithms**, Montgomery's collaboration with Pokrovskiy (Birkbeck) and Sudakov (ETH Zurich) led to the award of the 2019 European Prize in Combinatorics. Long-term visits hosted by Kühn and Osthus, funded by the Swiss National Science foundation (Kupavskii, Princeton IAS), Deutsche Forschungsgemeinschaft (Joos, Hamburg) and Sao Paulo Research foundation (Jie Han, Rhode Island), all led to joint papers. Kühn and Osthus were recognised for their fundamental contributions to research through the LMS Whitehead Prize in 2014, and the RS Wolfson Research Merit Award (Kühn 2015).

A key collaboration in **Geometry and Mathematical Physics** with the University of Alberta (Favero - Canada Research Chair; Doran - former Site Director of the Pacific Institute of Mathematical Sciences) led to seven co-authored papers with Kelly, including the proof (*Amer. J. Math.* 2017) of a ten-year-old conjecture of Batyrev and Nill. A further highlight was a Leverhulme Trust-funded visit by Joshi (Vice President IMU) to work with Mazzocco.

In **Algebra**, Craven with Dudas (CNRS) and Rouquier (UCLA) determined the Brauer tree for unipotent blocks of groups of Lie type (JEMS). With Oliver (Paris) and Semeraro (Leicester), Craven classified reduced fusion systems over p -groups with abelian subgroups of index p (*Adv. Math.*). With Brundan (Oregon), Goodwin exploited the Whittaker coinvariants functor for general linear Lie superalgebra to obtain important consequences in their representation theory (*Adv. Math.*). A further major success is Shpectorov's collaboration with Hall (Michigan), introducing *axial algebras* (Sec.1.3).

Active collaborations in **Topology and Dynamical Systems** include Baker's work with Alcaraz-Barrera (San Luis Potosi, Mexico) and Kong (Chongqing University, China), resolving several open problems of Erdős on base q expansions (*Trans. Amer. Math. Soc.* 2019). Good hosted Marie Skłodowska-Curie Fellow Meddaugh (Baylor). Their work characterising shadowing in dynamical systems in terms of shifts of finite type is a significant breakthrough in the field (*Inventiones* 2020; 19 citations as of March 2021).

Bespalov's recruitment (2013) to **Numerical Analysis** enabled an EPSRC-funded collaboration with Silvester and Powell (Manchester) on PDE problems stemming from uncertainty quantification. Petrovskaya's UoA-supported impact acceleration project is in collaboration with Harper Adams University.

A key theme in **Mathematical Optimisation** is Kocvara's PENNON algorithm for conic optimisation (Sec.1.1), the PENLAB open-source software developed with NAG, and **Impact Case Study** PENCOR, developed with Stingl (Erlangen) and Allianz. To date, PENLAB has registered more than 1900 downloads worldwide. In addition, the Horizon 2020 MSCA-ITN project POEMA targets new approaches to polynomial optimisation (Birmingham PI Kocvara, €4M, 10 EU Universities and 4 industrial partners). Two joint

research projects (EPSRC and FMJH-PGMO) with STFC-RAL, Namur and Toulouse focus on multilevel methods for very-large scale optimisation.

In addition to local collaborations in **Mathematical Biology and Healthcare/SMQB** and emerging links with Marseille (Sec.3.2), D. Smith's collaboration with Susana Lopes (Lisbon Medical School) led to an invited *Annual Review of Fluid Mechanics* paper. Montenegro-Johnson collaborates with SMEs Actronika, Ultrahaptics (Horizon 2020) and Cellink. Jabbari works with Krachler (McGovern Medical School, Texas), and Dyson has a long-standing collaboration with Nottingham's Centre for Plant Integrative Biology (e.g., *Nature Plants* 2017). The group is the leading node in the Biologically Active Fluids SIG of the EPSRC UK Fluids Network, co-organising workshops since 2017, developing online resources and hosting an international seminar series during the Covid pandemic.

In **Nonlinear Systems and Continuum Mechanics**, the group's recognised leadership in Bubble Dynamics and Free Surface flows is exemplified by Q. Wang's collaborations with Chinese experimental groups (Sec.3.4) and his EPSRC-funded research with Walmsley (Dentistry, Birmingham) on ultrasonic cleaning of dental appliances. Other key examples include Shikhmurzaev and Petrovskaya's EPSRC-funded project with Schlumberger Gould Research (Cambridge) on oil recovery and Shikhmurzaev's work-package leadership of a Programme Grant on developing a new generation of additive manufacturing processes with the Centre for Advanced Manufacturing (Nottingham), University of Warwick and eight industrial partners. Tzella led two EPSRC network-funded workshops (Birmingham and Warwick) and Uddin has undertaken KAUST-funded visits and joint-PhD supervision with Thoroddsen.

Nearly 150 papers have been published this cycle with co-authors from other disciplines, internal and external to the University, by 20 colleagues from both Pure and Applied themes. These collaborations encompass around 10 different academic disciplines and sub-fields. In addition to more conventional mathematics journals, staff publish in a broad range of interdisciplinary journals (e.g., *PNAS*, *Nature Communications*, *Physics of Life Reviews*) and subject-specific journals (e.g., *Nature Plants*, *Developmental Cell*, *ACS Synthetic Biology*, *Insects*, *mBIO*, *Ocean Engineering*, *PLoS Pathogens*, *Human Reproduction*, *Respirology*, *Ultrasonics*).

4.2 Interactions with wider society and industry

In addition to the industrial links mentioned in Sections 1.2, 2.1 and 4.1, the UoA's interdisciplinary activities extend more widely; examples include, Actronika, Ultrahaptics, Linear Diagnostics Ltd, Esmart Systems, Hamilton-Thorne, Procter and Gamble.

A key focus is the integration of mathematical modelling and experimental work. D. Smith, Jabbari's and Spill's groups involve PDRAs working extensively in both wet laboratory biology alongside mathematics, enabling an ideal cycle of "models informing laboratory work informing models". Terry and Woldman apply their models extensively to clinical EEG data.

Our Public Engagement Team, established during this cycle, is developing broad societal interactions. Montenegro-Johnson, Jabbari and PDRAs Cupples and Gallagher developed a permanent interactive exhibit at Birmingham Thinktank. This explores how soft microscale robots may be used to treat illnesses, using a remote-controlled robot and a playable video game to bring the theme's research to life. The exhibit combines Montenegro-Johnson's work on soft, transforming microbots (EPSRC Bright Ideas grant) with Jabbari's work on Antimicrobial Resistance (BBSRC grant), and Gallagher's research on sperm motility imaging. The project represents a unique example of researcher-undergraduate interaction, as the videogame was developed by the University Game Development Society. Terry's

establishment of SMQB brings a two-way dimension to public engagement with mathematical biology and healthcare research, building on his success with 'Beyond My Control', a theatre production to explore life with epilepsy and the impact that research can have. For example, supported by a SMQB seed-corn grant, D. Smith and Gallagher work with artist Vicky Roden to develop exhibits about patient experiences with hyperthyroidism and translational mathematics research.

The flagship Birmingham Popular Maths Lecture Series showcases the UoA's activity (13 Category A staff gave lectures this cycle), in addition to outstanding external presenters (e.g. Nira Chamberlain, Martin Hairer, Jennifer Rogers). Wider advertising (e.g. to 620 schools/sixth forms) has resulted in larger general public audiences (an average of 206 in 2020/21 per lecture compared to 56 in 2013/14). In 2020 Kombrink gave a public talk, broadcast live across China. Goodwin was an LMS Holgate Lecturer (2016-19). To give a representative sample, excluding popular lectures, our staff reached 2,584 UK 12-18 year-olds in the period Feb. 2019-Jan. 2020.

Looking ahead, we are also developing exhibits for The Exchange - a £40M University investment for showcasing research located in the city centre (4.2.2-REF5a) - and the Commonwealth Games Cultural Programme. Other potential exhibits include VR visualisation of modelling of plant root growth (Dyson).

Recognising the opportunities provided by social media, we have produced videos for Facebook, Twitter, Instagram, and LinkedIn showing academic staff talking about their research and its impact. For example, during Mathematics and Statistics Awareness Month 2019, academics and PDRAs from different stages of their careers were filmed talking about their research.

Engagement with external organisations includes Good and Jabbari's regular invitations to talk at The Training Partnership's national Maths in Action Days, reaching several hundred Sixth Formers at each event. Following a Birmingham City Council campaign for nominations from the public, Jabbari was selected for inclusion in a book about 30 inspirational women of Birmingham. Montenegro-Johnson is the lead scientific advisor for a Jonathan Hopkins sci-fi film (currently at screenplay phase). Craven has collaborated on several newspaper articles including a piece in *The Guardian* exposing statistical flaws in the Government's use of healthcare data. Craven and Goodwin have been interviewed by the *BBC* (additionally *ITV* and *Sky News* for Goodwin) on statistics related to Parliamentary elections and the National Lottery, respectively.

4.3 Conferences and research events

The UoA has fostered a culture of organising leading research events, including those led by PGRs (Sec.2.6). In 2015, we hosted the LMS-EMS mathematical weekend to celebrate their 150th and 25th anniversaries. Annually, we host a range of workshops and conferences, for example Groups St Andrews (2017) and the 27th British Combinatorial Conference (2019), which are the leading UK-based conferences in their respective fields. Events such as the BBSRC/EPSRC Multiscale Biology Study Groups (Sec.2.6), actively promote the formation of new collaborations, and have led to several outputs, including novel approaches to estimate Palaeolithic temperatures (*Clim. Past.* 2020), and to quantify glycocalyx function (*Phys. Rev. Fluids* 2020). Other significant events include the biennial IMA Conference on Numerical Linear Algebra and Optimization (2014, 2016, 2018); the LGBT+ STEMinar 2020 (Sec.2.7); and the EPSRC AIM-style workshop in harmonic analysis (2019).

Colleagues have led several external scientific programmes including the 2017 ICMS conference "Harmonic Analysis and its Interactions" (Bennett). Speakers included Larry

Guth, Malabika Pramanik, Elias Stein and Terence Tao. Goodwin led the 2014 ICMS conference on Algebraic Lie Theory. Speakers included Vera Serganova, Catharina Stroppel and Wolfgang Soergel.

Researchers across the UoA regularly receive invitations to speak at major conferences and events. Highlights include invited lectures at the 2014 International Congress of Mathematicians (Osthus and Kühn), an invited talk at CANADAM 2019 to c.400 participants (Carmesin) and invited talks at the British Mathematics Colloquium (Bennett, 2018; Kühn, 2014; and Mazzocco, 2018). There has been significant growth in the number of invitations to leading mathematical research centres, such as BIRS-Banff, MSRI and Oberwolfach (at least 20 researchers across the UoA).

4.4 Open access and editorship

The UoA has increased its representation on editorial boards for internationally leading general mathematics and specialist journals: *Beitraege zur Algebra und Geometrie* (Craven); *Bulletin and Journal of the London Mathematical Society* (Bennett, Craven and Maleva); *Combinatorica* (Kühn); *Discrete and Continuous Dynamical Systems* (J. Li); *Discrete Mathematics* (Carmesin, Osthus); *Electronic Journal of Linear Algebra* (diamond OA; Sergeev); *International Journal of Computer Mathematics* (Németh); *International Journal for Uncertainty Quantification* (J. Li); *Journal of Combinatorial Designs* (Kühn); *Journal of Combinatorial Theory A* (Kühn); *Journal of Group Theory* (Parker); *Journal of Hydrodynamics* (Q Wang); *Journal of Optimization Theory and Applications* (Németh); *Mathematika* (Bennett); *Optimization Methods and Software* (Kocvara); *Quarterly Journal of Mathematics* (Bennett); *Proceedings of the Royal Society Edinburgh A* (Gutierrez); *SIAM Journal on Discrete Mathematics* (Kühn); *Transactions of LMS* (gold OA; Craven, Maleva). Kühn is a founding editor of the new diamond open access journal *Advances in Combinatorics* which aims to be the leading journal in the area.

4.5 Citizenship

Members of the UoA have roles in various mathematical and learned societies:

- British Combinatorial Committee: Mycroft (2017-19); Treglown.
- European Mathematical Society: Mazzocco (Council).
- Heilbronn Institute: Kühn (Advisory Board, 2015-18).
- Isaac Newton Institute: Dyson (Scientific Advisory Panel for the Newton Gateway to Mathematics).
- IMA: Grove (Honorary Secretary, Education; Executive Committee; Council); Mazzocco (Research Committee); D. Smith (West Midlands vice-chair).
- International Centre for Mathematical Sciences: Mazzocco (Advisory Board).
- LMS: Bennett (Prize Committee, 2020/21); Kelly (Women in Mathematics Committee); Kühn (Prize Committee, 2018/19); Mazzocco (Nominating Committee); Parker (Chair of Early Career Committee and a Regional Organiser); Petrovskaya (Society Lectures and Meetings Committee).
- Real Sociedad Matemática Española: Reguera (Secretary of International Relations).
- RS: Craven and Goodwin (International Exchanges); Dyson (Newton International Fellowships).

Unit-level environment template (REF5b)

Shpectorov is an Athena Swan and Race Equality Charter panel member, and LMS Mentoring African Research in Mathematics grant holder (2016-18) with Bernardo Rodrigues (QwaZulu-Natal); activities have included running a summer school in Durban (2018) and joint PGR supervision.

Eight staff are EPSRC College members; senior colleagues regularly serve on EPSRC panels, and Terry was a member of the Healthcare Technologies Strategic Advisory Team until 2020. Birmingham has been represented every year (except 2014) on Mathematics Prioritisation or Fellowship panels in the current cycle. Kühn was an author of the 2016 EPSRC Combinatorics landscape document.