

Institution: University of Central Lancashire
Unit of Assessment: UOA10 Mathematics
1. Unit context and structure, research and impact strategy

Context

REF2021 represents the first submission to the Mathematics Unit of Assessment from the University of Central Lancashire (UCLan). Whilst Mathematics has been taught at UCLan for over 50 years, it is only over the last decade and specifically during the REF2021 assessment period that the University has strategically promoted the research development of the subject. Mathematics research at UCLan has now progressed into a small but active group. To grow our reach and sustainability, we have proactively developed and enhanced our networks with other mathematicians and the wider public. As a result, we have published internationally recognised research articles, obtained prestigious funding awards such as EPSRC and Leverhulme, and successfully inspired pupils and the general public to engage with mathematics.

The Mathematics Research Group (MRG) currently has four members [Anscombe, Daws, Penazzi and Powles] with one more member active during the REF period [Kestner]. It has evolved across four intertwined specialisms: model theory, topological dynamics, algebraic oriented functional analysis and acoustics; complemented by additional work on mathematical pedagogy and public engagement with research. The MRG members have instigated or are part of a variety of collaborations, interdisciplinary and specialist, nationally and internationally.

The MRG is embedded fully within the Jeremiah Horrocks Institute (JHI) for Mathematics, Physics and Astronomy. The Institute is one of UCLan's longest standing research units, delivering Physics submissions to every research assessment exercise since 1992. As an integral part of this lively research culture the MRG has access to research networking, external seminar speakers, visitor travel support and internal JHI research funding (for example for postgraduate research students and conference travel). In particular, the JHI has a long history of successful external engagement with the local community via its strategic outreach programmes that the MRG are now part of. Through its inclusion within the JHI the MRG's resources, networks and collaborations are significantly enhanced.

The MRG research environment is further extended through its regional and national specialism networks, for example the Model Theory community. These act as an "extended department" for ongoing research collaborations, specialist training of postgraduate students, as well as the organization of conferences. In addition, the MRG is fully integrated into a larger Mathematics teaching team across the JHI (approximately 10 FTE) including teaching only staff and researchers in both Physics and Astronomy. Notably this includes a team of solar physicists (e.g. Brown, Bewsher) and teaching staff (e.g. Bowman) who, whilst not all are currently research-active in Mathematics, have been active in mathematics outreach and public engagement programs. This broader team has fostered a positive community around the MRG, extending and sustaining its networks. Bewsher, is for example, Fellow of the Institute of Mathematics and its Applications (IMA) and Council member and Chair for the North West IMA branch.

Delivering the REF2021 Strategy

This submission of UOA10 Mathematics in REF2021 is the result of a conscious decision to instigate a step change in the development and delivery of University support for this key discipline during the REF period (2014-2020). Our research strategy focused on five core principles:

1. Establish and grow the MRG with the appointment of research active mathematicians.
2. Produce high quality research output in, and secure funding opportunities for, the MRG's areas of specialist interest.
3. Maintain existing specialist collaborations and begin fostering targeted new networks to increase the profile of and sustain a thriving research group.

Unit-level environment template (REF5b)

4. Embed the MRG within the JHI as an integral part of the wider research ecosystem to enable interdisciplinary, cross institutional partnerships.
5. Generate impact opportunities in mathematical education and public engagement with research.

Subsequently, during the census period the institution succeeded in building research capacity through the recruitment of researchers Kestner, Penazzi, Anscombe, Daws. The MRG has become an established dimension within the culture of the JHI. This has enabled a relatively small set of mathematicians to obtain a level of support comparable to much larger centres.

Our position within JHI is complemented by external, long established collaborative networks. Kestner, Penazzi and Anscombe are embedded members of the Model Theory community. In particular, they engaged with the Leeds and Manchester in forming LYMoTS (Lancashire Yorkshire Model Theory Seminar), which regularly features international researchers. Daws is active in the functional analysis community with local groups in Leeds and Lancaster. His EPSRC funded project is jointly delivered with the University of Glasgow. Powles has continued his work with collaborators in both Keele and Southampton. As outlined below, interdisciplinary opportunities have arisen with outdoor and experiential learning alongside health and sustainable development. The areas of mathematical education and public engagement have also prospered.

Future vision and strategy for the MRG

The vision for the MRG future research activity is centred on the following three strategic objectives:

- Building on the trajectory of the current areas of research expertise and collaboration including:
 - Quantum groups, in particular, the operator algebraic approach to (locally) compact quantum groups, and non-commutative objects such as quantum graphs, together with links to quantum information theory, furthering the work on the EPSRC grant, "Quantum groups in action".
 - Model theory and applications to topological dynamics, number theory and algebraic fields, in particular with the study of valuations; and continuous model theory with links to abstract harmonic analysis and Banach algebra theory.
 - Aeroacoustics, specifically, the study of scattering and turbulent flows.
 - Mathematics education including mathematical anxiety, development of confidence and mathematical resilience in school pupils and in the higher education sector and supporting adults in their use and understanding of mathematics.
- Broadening the MRG research base through interdisciplinary partnerships across UCLan's research centres and institutes, including engagement with the following:
 - Big Data and Artificial Intelligence through UCLan's investment in a Data Innovation Centre, led by Professor George Ellison recently appointed from the University of Leeds.
 - Lancashire's flagship Engineering Innovation Centre, aligned to the local industrial strategy.
 - UCLan's Research Centre for Global Development, led by Professor Nicola Lowe, to address targeted elements of the United Nations Sustainable Development Goals.
 - Supporting the development of a university-wide research centre for Education which can place the mathematical education research of the MRG within the larger set of educational initiatives of the institution.
- Bolstering the reach and significance of the MRG's impact, driven through the framework of the above activities.

Unit-level environment template (REF5b)

Subsequently, the intended UOA's strategic deliverables for the next REF period are planned to include:

- Academic recruitment. Strengthening the MRG by recruiting new academic researchers aligned with ongoing research expertise (first starting in January 2021).
- Investment in the research student experience and recruitment. Establishing an annual Undergraduate Research Summer Internship and the funding for a biannual Mathematics PhD studentship.
- Deepened and extended collaborations. Developing new multidisciplinary partnerships as a way to consolidate the trajectory of recent successful collaborative grant applications with diversified funding streams and production of high-quality research outputs.
- Increased exposure and recognition for the MRG nationally and internationally. Delivering invited seminars, attending targeted conferences, organising and hosting events in mathematical logic and mathematical education.
- Expansion of pedagogical research and relevant public engagement activities. Galvanising routes to research impact across a range of communities both regionally and internationally.

Embedding Impact

To achieve sustained, targeted impacts at regional, national and international levels, the MRG chose to focus its energies in two areas during the census period: (i) experiential learning and engagement with mathematics; and (ii) interdisciplinary public engagement projects. This strategy has allowed us to connect with a wide range of beneficiaries, facilitated by internal seed funding, targeted partnerships and external funding, for example from the Science and Technology Facilities Council (STFC). Our contributions to these areas are outlined in brief here, and in more detail in Section 4.

Experiential learning and engagement with mathematics. Mathematics anxiety is a widespread phenomenon which is a known limitation to the development of a country. Promoting educational methods which foster mathematical resilience contributes to the UN Sustainable Development Goal 4 (Quality Education) and to 8 and 9 (Decent work and economic growth and Industry, Innovation and Infrastructure). It is also relevant to the UK Government's Industrial Strategy, which seeks to address the mathematics skills gap in order to build prosperity. Therefore, Penazzi studied the role that outdoor and experiential learning can take in the support of the understanding of mathematics and the engagement with the subject. This research explored a variety of avenues, from the initiation of outdoor courses for Higher Education students in Mathematics through to the development of teacher training programmes on the use of 'Experiential Mathematical Activities' for primary and secondary school teachers both in the UK and in Benin. For this latter project the aim is to increase the undertaking of numerically based secondary school routes in African schools and thus nurture a more mathematically skilled population which can better foster economic development.

Interdisciplinary public engagement projects. Building on the agendas outlined above, Mathematics at UCLan have helped to inform a wide range of public outreach activities aimed at improving levels of awareness and engagement with science, technology, engineering and maths (STEM) subjects. These engagement activities have been undertaken as part of wider multidisciplinary projects, a strategic decision made to collaborate with University colleagues in the JHI and beyond to optimise opportunities available both regionally and nationally.

Key to the MRG's successful engagement across disciplines and audiences has been to place mathematics in familiar and relatable contexts to break down pre-conceived barriers and learning anxieties. As a result, MRG staff have inspired children from disadvantaged backgrounds through activities such as the annual Lancashire Science Festival (LSF). Specifically, staff have delivered talks on mathematics and the production of our most beloved animated characters (*'Maths, Disney and Pixar'*) as well as the design of rollercoasters. In addition, Anscombe was central to the production of a UCLan-published multi-disciplinary popular science book entitled *'Unmasked: the Science of Superheroes'*.

MRG's future impact strategy

In line with the wider MRG strategic aims, impact will play an increasingly important role in the choice of how the Mathematics research will be undertaken and applied. This strategy will build on our existing networks and capacities and expand the work we do into new distinctive areas.

- Mathematical pedagogy. This will include further development of engaged research into mathematical pedagogy. Penazzi will be continuing his collaboration with a hub of primary school teachers in Benin. Although hampered by COVID-19 related restrictions, this project already shows significant evidence of the positive impact of experiential learning on the mathematical resilience of students. The use of experiential learning in the teaching of mathematics is demonstrating to be an effective tool for teachers. A related teacher training course for national rollout across Benin, as well as to neighbouring countries, is the natural development and extension of this work.
- Health sector impacts. The use of experiential learning has helped Non-Medical Prescribers (NMPs) returning to education. Mathematics anxiety is a known hinderance for people starting in the profession. Addressing these skills gaps is essential to meeting the shortage of health professionals. Recent articles by Penazzi show successful routes to increase confidence in NMPs. Penazzi, with Powles, plan to extend this work in collaboration with the UCLan School of Health to (i) other NHS health practitioners to further develop their mathematical resilience; and (ii) a public awareness programme focused on understanding the data, graphs and projections, an issue particularly prominent given the display of data during the COVID-19 outbreak.
- Manufacturing impacts. Powles has in the past collaborated with Rolls Royce, and his current research on aeroacoustics will be an impact avenue to be explored in the mid to longer term. To that extent, the newly formed Engineering Innovation Centre can provide the right environment with Engineering colleagues to facilitate this work as part of a wider UCLan offering to relevant local and regional industries.
- Public engagement. Given recent success in this area, public engagement and outreach will also continue to be a focus of the MRG's impact activity. Due to the Covid-19 pandemic restrictions, a considerable number of impact activities were adversely affected. Promotion of the '*Unmasked: the Science of the Superheroes*' book will continue, engaging new audiences with mathematics at libraries, literary festivals and comic cons as well as at "traditional" science festivals. The MRG will continue to play an active part in the Lancashire Science Festival and our engagement programmes will be broadened to encompass the areas where multidisciplinary research opportunities are developing.

Supporting open research

The MRG fully supports and engages with UCLan's research policies on 'Open Access' and 'Data Sharing', covering the three REF2021 requirements of Deposit, Discovery and Access. Staff are responsible for ensuring their own compliance alongside the University Open Access team that supports this process by promoting awareness, registering new outputs, uploading author accepted manuscripts and monitoring wider OA policy adherence.

With regard to the criteria of 'Deposit', outputs are stored on the internal University's repository, Central Lancashire online Knowledge (CLOK) within three months of journal acceptance. Moreover, staff in the MRG have a culture of submitting their preprints to the repository ArXiv on submission and update them on acceptance. Regarding the criteria of 'Access', material is presented which enables download, readability and access to text and adheres to the Creative Commons Attributions Non-Commercial Non-Derivative (CC-BY-NC-ND) licence.

Unit-level environment template (REF5b)

Finally, concerning the ‘Discovery’ requirements, the MRG expands the REF2021 open access remit. Search engines guide the user to locating open access material, which is bibliographically presented on CLoK whilst Google Scholar searches automatically direct to the ArXiv submissions. Penazzi’s, Kestner’s and Anscombe’s articles also feature on the FP6 Marie Curie Research Training Network in Model Theory and its Applications (MODNET) website (available at www.logique.jussieu.fr/modnet/Home), which is currently the main online point of contact for the model theory community, including a newsletter that regularly updates the MODNET subscribers of new preprints.

Research ethics and assessment of risk

Working with communities, in particular in lower-income countries, the MRG needs to be mindful of the ethical implications of the research being undertaken. UCLan was the first University in Europe to sign up to the high ethical standards as per the Global Code of Conduct for Research in Resource-Poor Settings. Researchers must gain ethical approval for any research involving human participants (as in the case of pedagogical research), with ethics submissions directed to the University’s Ethics Review Panels, which has delegated responsibility for ethical review and approval from the University’s Ethics and Integrity Committee. UCLan is a member of the UK Research Integrity Office (UKRIO) and signatory to the UK Concordat to Support Research Integrity. Training in research integrity is mandatory for all researchers and a robust system of governance and oversight of ethics and integrity is in place through the school and faculty committees for Ethics and Integrity. This is supported by a programme of dissemination of good practice across the UCLan academic body.

In particular, pedagogical research and outreach activities can involve the participation of staff and students at events off campus. Any off-site activity is properly risk assessed with everyone working in schools and settings with vulnerable persons DBS checked and trained in safeguarding to an appropriate level. Penazzi is member of the UCLan Off-Campus Activity Group which develops processes and procedures to ensure the safety of students and staff working away from the University (e.g. on placements).

2. People

This UOA10 submission comprises four mathematicians (Anscombe, Daws, Penazzi, Powles). Two of the researchers (Anscombe, Daws) have been recruited since REF2014, and a research-active model theorist (Kestner) moved on from UCLan to Imperial College during the REF2021 assessment period.

Staff development strategy - mentoring and support

As a signatory to the Concordat to Support the Career Development of Researchers, UCLan recognises its commitment to supporting researchers “beyond the current contract”. The University does not employ staff on zero hours contracts and has more staff on a permanent contract than the sector average.

The MRG along with the wider Mathematics team are integral to the Jeremiah Horrocks Institute (JHI). There is significant complementarity in the teaching, research, and outreach across the core JHI subject areas. The strategy for staffing Mathematics has weighed both teaching and research expertise. All staff are expected to have a PhD on hiring and to obtain a Fellowship of Higher Education Academy (FHEA) or equivalent through a targeted UCLan study programme before being considered for promotion to senior lecturer. Research active staff are also active members of the London Mathematical Society (LMS) and the Institute of Mathematics and its Applications (IMA).

The MRG works with colleagues in the JHI to provide an inclusive, collegial and stimulating working environment for all academic staff and students. Newly arrived staff are provided a mentor from the Mathematics Teaching team as well as a JHI research active professor to help them settle into their

Unit-level environment template (REF5b)

job role and the new environment. Moreover, members of MRG maintain contact with previous mentors in their discipline who continue to undertake a guiding role; for example, Penazzi with Pillay (Notre Dame), Kestner with Macpherson (Leeds) and Anscombe with Koenigsmann (Oxford).

A formal structure for discussion and advice for all academics is provided by the University-wide appraisal system. Two appraisals per year are carried out by JHI research active professors, where a yearly plan and longer term 3-5 years academic goals are explored together. The discussion includes building individual career progression, increasing and maintaining elements of international research standing, as well as preserving research/teaching/admin workload balances. All appraisers undergo training for their role, including unconscious bias training.

In addition to this, at University level, a full programme of staff development is available for all career stages. For example, this includes postgraduate supervision training, training on writing grant proposals and development of research management skills. Early career researchers in particular are actively encouraged to make use of these opportunities to growth their research independence and gain external research funding. Associated research centres with whom the MRG has a connection give access to other specialised mentors, for example Dr Davies from the Centre for Collaborative Learning has provided support for writing grants focused on pedagogy in mathematics.

Staff are expected to attend external professional workshops and seminars (e.g. EPSRC Early Career Network events). There are academic career progression pathways through a number of routes whether that be research, teaching or innovation. There are a range of thriving staff networks, under the umbrella of the Equality, Diversity, Inclusion, and Communities team (see MRG's involvement below).

Since 2015, the MRG has been successful in regard to a number of promotions with four members being awarded Senior Lecturer status (Daws, Kestner, Penazzi, Powles). All were supported by their appraisers to develop individual career progression plans. Other members of wider Mathematics course team have also been promoted: Bewsher (to Principal Lecturer) and Brown (Reader). These promotions must all be applied for and are not granted merely on the cumulative time the individual has been undertaking a certain role.

The MRG members play vital roles across the fabric of the institution, ensuring that the group engages in strategic activities that shape the research environment. Our staff actively participate in a number of institutional level boards and panels:

- Penazzi is a member of the International Business Development Group and of the Off-Campus Activities Group.
- Penazzi and Powles are members of University Review Panel (URP), which validates and quality assures courses run and/or accredited by UCLan.
- Powles is a member of BEST (Building Essential Skills Together), a group which identifies gaps in knowledge in numeracy and writing skills within starting cohorts across the University and supports students to overcome them.
- Penazzi mentors and assesses FHEA applications.
- Since 2018, Anscombe has been co-chair of the Staff LGBT+ Network and a member of the UCLan Equality and Diversity Executive Group, organising University-wide LGBT+ events.
- Daws is a member of the School Athena Swan committee.

Interaction among all JHI staff including post-graduate research students is promoted via the weekly 'Donuts' meetings and seminars, which are followed by informal get-togethers with opportunity to talk with colleagues and the seminar speaker. Perhaps the main feature is the interdisciplinarity of these events, with mathematicians, physicists, and astronomers all giving talks and interacting together. Moreover, the Institute seminar included prominent Mathematics speakers; for example, in 2016, Prof. Jochen Koenigsmann (Oxford) addressed the Institute with '*On rational numbers*'.

Unit-level environment template (REF5b)

Also, in 2015, funding was provided by UCLan for Kestner to undertake a six-month sabbatical, which allowed her to spend time in South Africa collaborating with G. Boxall (leading to a publication in *The Journal of Symbolic Logic*).

Postgraduate students

Since REF2014 there has been one Mathematics PhD student completion (Thomas Kirk), supported by internal funding. Moreover, a second PhD student in the area of Solar Physics was co-supervised by Powles.

Progression of postgraduate research (PGR) students is monitored via an annual review system managed by the University's Graduate Research School; in addition, for PhD students there is the transfer process from the MPhil to PhD stage. Furthermore, PGR students are supported via a weekly programme of mathematics/physics/astrophysics-specific PGR Lectures given by the wider JHI academic staff, alongside regular mathematics seminars, a series of postgraduate-presented seminars and a comprehensive training programme provided centrally by the University. The latter includes extensive training at the start of their study with additional events and online training as they progress. New PhD supervisors themselves benefit from an induction programme provided at University level and Penazzi, Kestner and Anscombe have taken advantage of this. PGR students are also strongly encouraged to support the JHI's outreach activities by participating in public engagement events on campus.

Given all MRG members have membership of the IMA and the LMS, they have been able to direct students to formative events such as IMA meetings and conferences. Funding has been made available by the JHI that has frequently extended beyond the travel funding provided within a PGR studentship. For example, PhD student Kirk has maximised these opportunities and has presented his research at logic seminars (Manchester and Leeds), mathematics seminars (Birmingham) and in conferences (BPGMT). On top of this, in 2016 Kirk obtained a grant to spend a month in Munster at the academic school "Model Theory month in Munster". Moreover, he connected with the regional model theory community with easy access to seminars in Leeds and Manchester, the thrice yearly LYMoTS meetings and the annual British Postgraduate Model Theory (BPGMT) conference, and participation in conferences such as '*From Permutation Groups to Model Theory*', held at the ICMS Edinburgh in 2018. At an institutional level, Kirk presented at the Annual UCLan PGR Student Conference and was part of the University's Three Minute Thesis Competition.

Equality and Diversity

Since 2009, UCLan has had in place a Single Equality Scheme to demonstrate the institution's commitment to meeting the Public Sector Equality Duty and to embed equality across the organisation. In 2016 UCLan updated the objectives and produced an Equality, Diversity and Inclusion Strategy for 2016-2020. The EDI Strategy has four Equality Objectives:

- Enriching our culture of valuing and engaging people;
- Ensuring fair processes and inclusion;
- Empowering People (protected groups);
- Embedding diversity dignity and wellbeing.

UCLan is an inclusive employer and supports a highly diverse staff and student body including 14.1% BAME, 7.3% staff with a declared disability, and employees from all continents.

The University is a Level 1 Disability Confident Employer and has been a signatory of the Mindful Employer Charter since 2012. The Disability Staff Network provides peer support for staff who consider themselves disabled and is a vital part of ensuring the University is a mindful employer through membership of institutional level E&D groups. There has been support and care for members of the MRG across the range of protected characteristics.

Unit-level environment template (REF5b)

It is impossible to make meaningful or sensitive commentary around the diversity of this small group beyond observing that there is gender representation: in regard to the wider Mathematics team, in the period 2015-2020, approximately 30% are female. Overall, the JHI has a very good representation of women among academic staff which extends to leadership roles (two out of six professors are female) and has actively focused on gender balance in staff recruitment and support strategies for many years. This approach is embedded within the annual appraisal system as well as specific mentoring opportunities, alongside School and University-wide E&D activities.

MRG staff take an active role in supporting UCLan's Equality and Diversity work. Members has been co-chair of the Staff LGBT+ Network and a member of the Equality and Diversity Executive Group since 2018. They organized events at UCLan for the LGBT History Month in February 2020, culminating with the invitation of the LGBT+ advocate and motorsport champion Charlie Martin.

The University has recently been awarded Athena Swan Bronze, to which Daws actively contributed as member of the working group. With the creation of the new School of Natural Sciences in August 2020, E&D activities are taking place within the School that will lead to an Athena Swan application for the specific subject areas that are now part of the new academic arrangement. The School has invested in this effort by dedicating 0.2 FTE of a new senior Principal Lecturer position to focus specifically on E&D.

3. Income, infrastructure and facilities

During the REF2021 period, the MRG has successfully obtained funding from a range of sources to support its research and impact activities. These include:

1. Leverhulme Research Project (£144,000) led by Kestner (since moved to Imperial), with Anscombe as Co-I. The grant equally supports Kestner and Anscombe, with additional support from UCLan (additional half of the support for staff time), and it employs a Postdoctoral Research Assistant, for three years, based in Imperial, and working with both Anscombe and Kestner. The PDRA's funding has supported several extended visits to work on-campus at UCLan.
2. EPSRC Standard Grant (£51,885), led by PI Daws. This grant supports Daws, and is part of a wider project in collaboration with Dr Voigt at the University of Glasgow (£263,000) which will fund a Postdoctoral Research Assistant who will be working with both Daws and Voigt
3. The LYMoTS network, joint between UCLan, Leeds, and Manchester, has been running since 2013. The grant, held at UCLan by Penazzi from 2013-2018, is £1500 per annum from the LMS.
4. The University has provided financial support to Mathematics research, on a competitive basis. For example, in 2017 Anscombe was awarded internal "Seed Corn" funding of £5000 in a competition to support Early Career Researchers
5. Penazzi and Anscombe both won LMS Celebratory Conference Grants on their appointment as Lecturers at UCLan (Penazzi - Model Theory, Topological Dynamics and Real Algebraic Geometry, 2015; Anscombe - Model Theory of Valued Field- 2017) – Approx. £500 each.

Members of the MRG have been supported for participation in research programmes. For example, Anscombe was financially supported by the Centre Émile Borel for a two-month participation in the trimester *'Model Theory, Combinatorics and Valued Fields'*, held in 2018 at the Institut Henri Poincaré. More recently she was awarded financial support to participate as a Research Member of the Mathematical Sciences Research Institute, Berkeley, in the semester *'Decidability, definability and computability in number theory'*, in 2020 (moved online due to COVID-19).

With a more impact focus, Penazzi was awarded £4K from Sigma to support his project "Experiential mathematical activities to build resilience". Anscombe with other UCLan colleagues across the Faculty of Science and technology was awarded £8450 from UCLan's Research Catalyst Scheme

Unit-level environment template (REF5b)

to create, design and print the popular science book *'Unmasked: The Science of Superheroes'*. This has led to further funding of nearly £23,000 from STFC to print 12,000 copies of the book for their national outreach initiatives.

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

Research Collaborations

Our collaborations are widespread;

- Anscombe has collaborators in number and model theory in Dresden and Muenster, Germany (Jahnke and Dittmann), Szczecin, Poland (Kuhlmann) and Oxford (Koenigsmann); her collaboration with Fehm, in Dresden, resulted in the writing of key articles in the realm of model theory of henselian valued fields, such as *'Characterizing diophantine henselian valuation rings and valuation ideals'*, in Proceedings of the London Mathematical society, and *'The existential theory of equicharacteristic henselian valued fields'* in Algebra & Number Theory. Moreover, Anscombe had visiting positions in Oxford (2019) and Berkeley, USA (2020).
- Daws has collaborators in functional analysis in Glasgow (Voigt and Schmidt), Lancaster (Choi) and the Czech Academy of Science (Horváth). As a leading figure in the study of compact and locally compact quantum groups, he has developed recent collaborations with Skalski in Warsaw, Poland, leading to articles such as *'The Haagerup property for locally compact quantum groups'* in Journal für die reine und angewandte Mathematik, and *'Around property (T) for Quantum Groups'*, in Communications in Mathematical Physics.
- Penazzi has collaborators in model theory and topological dynamics in the Notre Dame, USA (Pillay), Fudan, China (Yao) and Wroclaw, Poland (Gismatullin), with whom he authored several seminal papers in tame topological dynamics, such as *'some model theory of $SL(2, R)$ '* and *'Some model theory and topological dynamics of p -adic algebraic groups'*, both in Fundamenta Mathematicae.
- Powles has collaborators in Engineering in Southampton (Tester) and in Acoustics in Keele (Chapman), with whom he conducted accurate studies of sound fields generated in supersonic jet engines, the latest articles being *'Canonical Sound fields in the frequency-domain theory of supersonic leading-edge noise'* and *'Basic singular fields in the theory of impulsive supersonic leading-edge noise'*, both in Wave Motion.

Conference Organisation and Engagement

In 2014, Penazzi and Kestner organized the British logic colloquium and BLC PhD day at UCLan. Penazzi and Anscombe organized LMS-funded Celebratory conferences within two years of their appointment (Penazzi – *'Model Theory, Topological Dynamics and Real Algebraic Geometry'*, 2015; Anscombe – *'New directions in Model Theory of Valued Fields'*, 2017)

Anscombe was a co-organiser of *'From Permutation Groups to Model Theory'*, held at the ICMS Edinburgh, in 2018, with funding from the ICMS, LMS, BLC, and NSF. Daws co-organised the Analysis stream of the BMC 2019.

MRG members are extremely active in national and international conferences: in this REF period, in excess of 40 research talks have been given at conferences and seminars external to UCLan. Highlights include: *'Axiomatizing denseness in real and p -adic closures'* at the Seminaire General de Logique, IMJ-PRG Paris (Anscombe, 2019); and *'Fields of algebras'*, at the Workshop on Harmonic Analysis and Operator Theory (Daws 2019). Additional contributions include Anscombe's chairing of the panel discussion at BPGMT 2017.

Leadership within the Academic Community

The MRG and the extended Mathematics team take a prominent role in academic leadership at a national level. Notably, for the IMA, Bewsher, in Mathematics teaching team, has been an elected council member (2013-2019) and North West Branch Committee member (2009-present) and Chair

Unit-level environment template (REF5b)

(2019-2020). Kestner was elected Treasurer of the British Logic Colloquium in 2015. Daws is editor of the conference proceedings of IWOTA (International Workshop on Operator Theory and its Applications). MRG members regularly referee manuscripts for academic journals and review grant applications.

Instigated prior to and continuing throughout the REF2021 assessment period, Penazzi and Kestner started a series of conferences which have determined the shape of the national network of model theorists. LYMoTS (originally the Manchester Leeds Model Theory Seminar) was started in 2008 by Penazzi in Leeds and Tressl in Manchester and extended to UCLan following his appointment as Lecturer. LYMoTS is an excellent example of a successful regional community of practice in the discipline. This inspired a version to be setup in the south of England (SEEMOD) which Kestner has expanded upon with her arrival at Imperial. The BPGMT (British PostGraduate Model Theory Conference, now BPGMTC), originally started by Penazzi and Kestner in 2011, has proven an excellent space for PhD students to share ideas, give seminars and receive positive and encouraging feedback from more senior academics. Despite the name it regularly attracts many international PhD students.

Engagement with society and the wider public

As outlined in Section 1, our approach to engagement has been strategically targeted to two foci (i) experiential learning and engagement with mathematics; and (ii) interdisciplinary public engagement projects.

Experiential learning and engagement with mathematics

Penazzi has promoted the use of Experiential Mathematical Activities (EMAs) to a wide number of beneficiaries. This work stems from his interdisciplinary research with outdoor learning and in schools. These activities have been delivered both on and off campus, with the aim of motivating students in the study of mathematics. He trained teachers on the use of EMAs (both in the UK and Benin) and mentored UCLan students who then moved onto a PGCE Mathematics. Benefiting from UCLan's relationship with the Conversation he wrote an article for the platform entitled '*Maths: six ways to help your child love it*' which has had over 18000 reads in English and over 56000 in French.

Interdisciplinary public engagement projects.

As outlined in Section 1, through the work of Anscombe and Bowman in particular, Mathematics at UCLan has informed a number of public outreach initiatives, playing an integral part in multidisciplinary projects. By working in partnership with the annual Lancashire Science Festival (LSF), the MRG has inspired children from disadvantaged backgrounds to engage in mathematics. With over 65K visitors since 2014, an audience analysis conducted by the UK Science Festival Network in 2017/2018 showed that LSF attendees with limited budgets or living in rented accommodation were overrepresented at the LSF compared to national averages. MRG members have presented interactive maths stalls, contributed to freely available school "Experiment Packs" and popular maths talks (e.g. '*Rocket to the Moon*' for the 50th Anniversary of the Apollo Landings).

A recent highlight is Anscombe's role as co-author of the UCLan-published multi-disciplinary popular science book entitled '*Unmasked: the Science of Superheroes*'. Through support from the Science and Technologies Facilities Council the book has now gone to every library in the UK and an accompanying website (www.unmaskedscience.com) has national curriculum related material for each science chapter.

The MRG have expanded their engagement beyond younger learners to broader audiences. It hosts an annual IMA Winter Public Lecture which draws roughly a hundred attendees. In March 2020 a scheduled Jeremiah Horrocks Public Lecture, with Prof. Caroline Series FRS (former LMS President) was postponed due to COVID-19 restrictions.

From 2021, the MRG will continue to expand and deepen its public engagement partnerships, whilst also utilising the infrastructure and networks hosted at UCLan to broaden its impacts into the public and private sectors through engagement with manufacturing and health stakeholders.