Institution: University of York

Unit of Assessment: 10 - Mathematical Sciences

a. Overview

The Department of Mathematics belongs to a coordinated grouping of science departments which promotes collaboration between disciplines. The Department's research groups, each with a focal seminar series, are: Algebra; Applied and Interdisciplinary Mathematics; Mathematical Physics (including Quantum Information and Foundations, Quantum Gravity, Quantum Integrability); Number Theory; Statistics; Stochastic Analysis and Mathematical Finance. Many staff are affiliated with multiple groups, collaborate across groups, or cross discipline boundaries. Some are based within the *York Centre for Complex Systems Analysis* (YCCSA), which has a core of joint appointments, including three Maths/Biology and one Maths/Chemistry.

b. Research strategy

The Department's research strategy is formulated by its Research Committee in association with medium- and long-term plans, informed by meetings of all academic staff, agreed and supported at University level, and implemented by the Departmental Management Team. The Department aims to maximise its impact in areas where it is a strong player internationally. It plans to selectively strengthen its world-leading groups, drive the development of smaller groups towards success and sustainability (in terms of staff, fellows, graduate students and grants), and support them to win substantial research funding. We aim to further strengthen interdepartmental and external collaboration and build additional capacity for this, in order both to enable flexible responses to new challenges and funding streams and to enhance interdisciplinary collaboration, impact and knowledge transfer. Planned initiatives include a university-wide *Centre for Quantum Information*. Valuable support is provided by our strong MSc/MRes portfolio (with more MSc students than comparable departments, approx. 80 per year), which we shall maintain and develop to provide income, supply PhD students and support external links.

During 2001-2007 the Department expanded significantly in the areas of classical applied mathematics, quantum information, mathematical finance and stochastic analysis, partly by incorporating seven leading staff from the defunct Hull department. Further, it was a founding member of YCCSA, a strategic move supported by a series of joint appointments with Biology and Chemistry. Since then our RAE2008 aspirations for 'moderate but steady growth' have been exceeded, and we have appointed twelve new staff to strengthen and bridge our research areas (see below and Sect. **c**). For example, no Statistics submission was made in 2008, but a strategic decision was made to appoint a professor and three other staff in this area, supported by a new MSc programme, creating a viable and thriving group of six staff. The positions resulted from our success in attracting outstanding candidates for institutional Anniversary Chair schemes, attracting long-term funded Fellows, and generating new income streams, principally from growth in student numbers. For 2014-20 a principal aim is to achieve commensurate growth across the department in grant funding and PDRA/F numbers, as set out below.

All staff are supported to pursue creative, distinctive long-term research goals, aiming for substantial papers of depth, significance and long-lasting influence. Overall, we aim for a stimulating, collegial and collaborative research environment.

Algebra

The work of the algebra group ranges from quantum groups through representation theory and algebraic groups to reflection groups, monoids, universal algebra and model theory. Supported by a series of PDRAs funded by EPSRC and others, its strategic aim is to build high quality links with Number Theory and Quantum Integrability, securing large-scale funding to enhance the group's distinctive identity and pursue the research goals described below.

A major research theme is to explore to what extent theory can be transferred from zero- to positive characteristic, *e.g.* in algebraic groups via geometric invariants and buildings (Bate, appointed in 2008, who has made significant progress towards proving Tits' Centre Conjecture) and in the representation theory of Schur and Brauer algebras (Donkin, in work directed towards a positive-characteristic analogue of the Borel-Weil-Bott theorem). This links with Nazarov, who has

used Yangian and quantized affine algebra symmetries to prove powerful new results in classical representation theory (linking with Quantum Integrability); he aims to build a duality between Cherednik algebras and toroidal quantum groups. Everitt's style is topological: he has developed the cellular cohomology of small categories with coefficients in a presheaf (which applies to buildings, connecting with Bate), and applied discrete groups to hyperbolic manifolds to provide a solution to the Siegel problem. He is currently developing a *White Rose* collaboration with Leeds and Sheffield to explore links between quantum topology and quantum information via knot theory, supported by an international team which includes Jones, Kauffmann, Turaev and Jackiw. His work on reflection monoids connects with Gould, who pioneered the study of restriction semigroups and endomorphism monoids of independence algebras.

Applied and Interdisciplinary Mathematics
The group's unifying approach is to employ mathematical rigour to reveal the underlying mechanisms of processes and phenomena, and to probe the mathematical descriptions to provide new understanding or predictions that can be tested. Subgroups have interests at the interface of mathematics, biology, physics and chemistry, developing new mathematics, computational methods and analytical tools for complex systems. Members include Delius, Ilin, Pitchford (Maths/Biol), Twarock (Maths/Biol), Vladimirov, Wilson (Maths/Chem) and A. Wood (Maths/Biol). In 2012, the group's strength and coherence were enhanced by the appointment of an Anniversary Chair, Bees (Maths). A distinctive strength is that many group members have dual expertise, allowing them to work across disciplinary boundaries, and this drives the group's multidisciplinary approach. The group collaborates strongly in YCCSA and York's new *Biological Physical Sciences Institute* (BPSI, founded 2013), which aims to facilitate interaction across the physical/life sciences interface. The group has won significant research funding from many sources, and aims both to lead and to participate in multidisciplinary large-scale grants (such as the Wellcome-funded *CIDCATS* CDT, of which Twarock is co-director).

Bees (EPSRC ARF to 2011) leads a new wet lab to study swimming microorganisms. He was the first to analyse dispersion of biased swimming cells in tubes, to measure and explain flows around individual stuck bacteria, and to probe theoretical and experimental aspects of bioconvection, moment expansions and biofuel optimisation. He has developed novel theory on speciation, structured populations, synchronisation and differential dynamic microscopy for cell motility assays. His work was featured in *Nature Methods* (9:1145, 2012) and as a *Nature Research Highlight* (*Nature* 474:544, 2011). Delius models ecosystems and extinction trajectories in microcosm communities, especially aquatic ecosystems. He created the first model of fish populations in which scale-invariance is fundamental, with significant implications for fisheries policy. Twarock's mathematical virology group, supported by over £1M of funding 2008-13, was used as a case study by the *Isaac Newton Institute*. Her new approach to virus structure (including *Acta Crystallographica* work selected as an IUCr highlight) offers a step-change over Caspar-Klug theory, and revealed a previously unrecognized scaling principle among viral components. Her work on virus assembly has contributed to a paradigm shift in our understanding of RNA. Another highlight is the work of Vladimirov on asymptotic and averaging methods applied to (especially biological) fluid dynamics. His new approach to oscillating flows offers significant improvement over matched asymptotics, with applications to steady streaming, especially in channels and with oscillating boundaries. He exploits these methods to study micro-robots (highlighted in *JFM Rapids* 716:R1, 2013), acoustics, turbo-machinery, and the swimming of micro-organisms. In an exciting recent example he showed that the 'liquid film motor' can be explained using novel small-scale applications of known electrohydrodynamic processes, without invoking exotic new science.

Mathematical Physics
This group has been strengthened by three new appointments: Rejzner, in Quantum Gravitation and Quantum Field Theory (QFT); Bostelmann, who connects this area with Quantum Integrability; and Colbeck (a University *Anniversary Lecturer*), who strengthens Quantum Information and its links both with Physics and with the new quantum-technology industry.

Quantum Field Theory and Quantum Gravitation. The overarching aims of the Quantum Gravity subgroup (Bostelmann, Fewster, Hawkins, Higuchi, Kay, Rejzner) are to improve our grasp of quantization, further extend the insights of Minkowski-space QFT to curved spacetimes (CST), and thereby deepen our understanding of quantum gravity. The group ranges from foundational and

conceptual to phenomenological questions, using techniques drawn from geometry, functional analysis, operator algebras and category theory. Bostelmann, Fewster, Kay and Rejzner form a strong and coherent group within the field of rigorous QFT, considerably increasing York's (and the UK's) international presence since 2008. The group now aims to increase its funding profile so as to become competitive for large-scale grants in the medium term. Research areas where the group is at the forefront include: quantum energy inequalities (QEIs) (Bostelmann, Fewster), gauge theory and quantum/linearized gravity in CST (Fewster, Higuchi, Rejzner), and the deep functorial approach to QFT and classical field theory in CST (Fewster, Rejzner). Contributions since 2008 include: the control of scaling limits in QFT (Bostelmann), extension of QEIs to interacting QFTs (Bostelmann, Fewster), the rigorous implementation of the Batalin-Vilkovisky formalism in CST (Rejzner), and the abstract characterization of global gauge symmetries (Fewster). Fewster's work on singularity theorems related to QEIs and Higuchi's work on the graviton vacuum in de Sitter were both Research Highlights of *Classical and Quantum Gravity*, in 2011 and 2012. Higuchi *et al.*'s 2008 review of the Unruh effect is a definitive contribution, with over 190 citations to date.

Quantum Information and Foundations. Busch**,** Colbeck and Weigert work on fundamental structures of quantum mechanics, aiming at a deeper understanding of the characteristics that single it out within a class of theories, and ways to exploit these in novel technological applications. A second goal is to elucidate the structure of the set of quantum observables, which is far less well understood than that of quantum states. Their research agenda builds on interactions with a wider York group from Physics, Chemistry and Computer Science, which plans to create a *Centre for Quantum Information*, for which they are working to secure financial underpinning from, among others, an EPSRC Programme Grant. The team maintains intensive collaborations with world-leading groups including at Cambridge, Hannover, Oxford, Turku and Zurich. Busch's results include new insights into fundamental limitations imposed by symmetries on position measurements, overturning previous beliefs. This work was highlighted by both *Physical Review Letters* and the *European Physical Journal D*, which said that 'with this result a long-standing open question [has] been answered'. Busch's work on the first rigorous formulation of Heisenberg's error-disturbance trade-off relation was featured as *Nature News* 418:419, 2013. Colbeck (whose work includes three papers in *Nature Physics*) has obtained novel insights into quantum randomness, with applications to quantum cryptography, specifically device-independent cryptographic protocols. Weigert has produced compelling evidence for the absence of more than three mutually unbiased bases (MUBs) in 6D Hilbert space, and a new perspective on the underlying existence problem by transferring it to the Hilbert space for a quantum particle. Busch has recently discovered a connection between certain measurements ('SIC-POVMs') and systems of MUBs via the theory of joint approximate measurements, with intriguing combinatorial features. Busch and Colbeck aim to develop novel uncertainty relations concerning joint measurability of incompatible observables and apply these to protocols for quantum information processing.

Quantum Integrability. Corrigan FRS, MacKay and Sklyanin (elected FRS in 2008) work on integrable models, using empirical mathematical calculation and discovery in theoretical physics to create new mathematics. A central goal is a complete classification of integrable defects and boundaries and their symmetries. Corrigan has found new classes of classical and quantum integrable defect, initiated a study of infinite-dimensional representations of quantum groups, and used them to find novel solutions of the boundary Yang-Baxter equation. MacKay's previous discovery of generalized twisted Yangians associated with integrable boundaries has proven to be the hidden symmetry of string worldsheet scattering from AdS/CFT D-branes, and led to a new, 'achiral' twisted Yangian. Sklyanin, one of the architects of quantum groups and the modern Bethe ansatz, has introduced a generalization of it which yields new results in combinatorics, and has constructed a hierachy of commuting charges in a 1D model of infinitely-many interacting particles. His current goal is to develop the Bethe ansatz further to allow particle merger and decay, and thereby reveal new algebraic structures (with Nazarov).

Number Theory

This group, singled out as a research strength in RAE2008, has subsequently been enhanced by the permanent appointments of Beresnevich (EPSRC ARF to 2010), Haynes (EPSRC CAF to 2016) and Zorin. Since 2008, members of the group have won £3M in research funding, including a recent £1.6M EPSRC Programme Grant, which also explores links between number theory and wireless technology. The group's central interests lie in Diophantine approximation and analytic

number theory including metric and transcendental number theory, Diophantine approximation on manifolds and algebraic independence theory, the theory of the Riemann zeta function and their connections to dynamical systems, ergodic theory, fractals and random matrix theory. The encompassing goal of the group is to create bold new frameworks and techniques to solve longstanding challenging problems such as the conjectures of Littlewood (1930) and Duffin-Schaeffer (1941), the generalised Baker-Schmidt problem (1970) for manifolds, and those surrounding Riemann zeta. They have made major advances, both in developing new theory and in solving long-standing problems. Highlights include: Velani *et al.*'s proof of Schmidt's Conjecture on the intersection of simultaneously badly approximable sets; Beresnevich's novel, general technique for detecting rational points near manifolds, leading to a coherent theory beyond planar curves; and Beresnevich & Velani's Inhomogeneous Transference Principle, a versatile framework that establishes the Inhomogeneous Baker-Sprindzuk Conjecture, and a major advance on the earlier work of Kleinbock & Margulis. Hughes (with Young) has calculated the twisted fourth moment of the Riemann zeta function, a result which is already having significant impact, for example in estimating large gaps between the zeros of Riemann zeta. Exploring a measure rigidity theorem of Lindenstrauss, Haynes (with Harrap) has initiated the application of the Baker-Wustholz method to prove the Mixed Littlewood Conjecture with pseudo-absolute values. By exploiting Schmidt games, Levesley *et al.* have established the 'mixed' analogue of the Schmidt Conjecture. Zorin's work in the theory of algebraic independence develops new, powerful techniques applicable in any characteristic, improving the earlier results of world authorities such as Mahler, Philippon and Nesterenko. By making use of fractal measures close to Lebesgue, Beresnevich, Haynes & Velani (with others) have made new and exciting contributions to the Duffin-Schaeffer Conjecture.

Statistics

Since 2008, the Statistics group has been rejuvenated with the appointment of Zhang (Chair & group leader) and three other staff, creating a sustainable group with full PhD, MSc and seminar programmes. Their further expansion, fully supported by the University, is integral to the department's long-term plan. Zhang works in nonparametric methods, and recently introduced a paradigm-changing nonparametric method for analyzing clustered data. His goal is to develop new statistical methods for high dimensional data, in which variable selection and feature extraction play pivotal roles. Another theme is time series: Knight, by constructing a spectral estimate hinged on a new nondecimated lifting transform, has created for the first time a method which copes with nonstationarity and missing data simultaneously. Li focuses on nonlinear non-stationary time series and longitudinal data analysis, with applications in climatology, economics and finance. Work on applied statistics includes the application of Bayesian methods to patients' perceptions of health states and 'quality-adjusted life years' (Kharroubi), and the development of indices of poverty and inequality and the analysis of fish recruitment data (Mazzi) ─ most recently applied to killer whales in an YCCSA collaboration which resulted in an article for *Science*.

Stochastic Analysis and Mathematical Finance

Work in stochastic analysis focuses on stochastic PDEs (SPDEs) and point processes, proving results motivated by, and significant for, applications from physics to economics. In SPDEs the goal is to understand the role of noise in the emergence of singularities in wave, Landau-Lifshitz-Gilbert and other SPDEs under constraints and with jump processes (Brzezniak, funded by the *Leverhulme Trust*). In cluster point processes (CPP), a new approach has been proposed, based on configuration-space analysis, and the aim is to use it to solve point processes which appear as distributions of interacting particle systems (Daletskii), connecting to Mathematical Physics.

The Mathematical Finance group works on American options and other derivative securities, developing the mathematics of transaction costs and other market imperfections, a longstanding problem of huge practical importance. Progress includes results on exercise times, arbitrage and hedging strategies (Roux and Zastawniak), and energy derivatives, volatility and dynamic risk, especially in environmental problems (Kang). Expansion of the group's research is a central plank of the Department's long-term plan. Kang's appointment is the first of a planned series, building on the group's success in MSc teaching, and strategically directed towards increasing world-class research capacity and bringing theory into practice. The group is supported by Advisory Board members from *Barclays Capital* and the *Institute and Faculty of Actuaries* (Sect. **e**).

c. People, including:

i. Staffing strategy and staff development

Academic Staffing. The Department fulfils its strategic aims by strengthening excellent groups, supporting smaller groups, and creating synergies and new connections between them (*e.g.* Bees' linkages between fluid dynamics, YCCSA, the BPSI and, via a new wet lab., with Biology). Appointments since 2008 (see Sect. **b**) include Bate, Bees, Bostelmann, Colbeck, Haynes, Kang, Knight, Li, Rejzner and Zhang. We intend to make professorial and other appointments to build broad strength and coherence across pure mathematics, especially in Algebra and Number Theory, and to strengthen coherence, interdisciplinarity and impact potential across applied mathematics, especially in Mathematical Biology, Mathematical Finance, Quantum Information, and Statistics. Our vision is shared and supported by the University: *e.g.* Bees' and Colbeck's appointments were institutional 50th Anniversary posts.

Career development. Our aim is to enable staff at all levels to realize their talents by producing work of depth and significance and thereby become world-class researchers with outstanding international profiles. For example, Beresnevich has been supported through his career in York as, successively, PDRA, EPSRC Advanced Fellow (AF), Reader and Professor. Twarock, a Marie Curie fellow at York early in her career, returned to York as AF and is now Professor. Support is given at all stages, in part through an annual performance review (by the PI, professor or HoD) which offers guidance on research plans and career advancement and is timed to precede and support the promotions procedure. In 2008-13 there have been 7, 3 and 7 promotions to Senior Lecturer, Reader and Chair respectively. Early Career Researchers (ECRs) have a dedicated mentor, a 2/3 teaching load and relief from administration, and follow a *PGCert in Academic Practice*. All colleagues benefit from a range of award-winning staff development courses.

Post-docs and fellows are an essential part of our research community. We aim that their stay at York should lift their career to new levels. The department attracts long-term EPSRC AF/CAFs and Royal Society URFs and supports them into academic careers─three have moved to academic positions since 2008 (Beresnevich**,** Twarock**,** Wilson), and two in 2001-07 (Delius**,** Velani)**.** Since 2008 the department has had a further 26 shorter-term PDRAs and independent fellows, 11 of these in post in October 2013. We immerse new post-docs in their group immediately, with seminars or research lecture series, reading/study groups, and encouragement to speak at regional (*e.g*. LMS scheme 3) and national meetings. Every post-doc has a mentor outside their immediate group, who (with the PI) provides research and career advice, finding and explaining openings for academic positions and supporting applications. Post-docs and ECRs benefit from training courses in career development, grant-getting, PhD supervision and other areas ─ the University's *Research Leaders' Programme* won the THE 2012 award for 'Outstanding Support for Early Career Researchers'. Post-docs are offered teaching opportunities, to the extent that they wish, with full mentoring, training and collegial support. The department has a full action plan to support the *Concordat to Support the Career Development of Researchers*, with recent actions including ensuring that all internal funding is advertised to all staff and allocated transparently. The department is especially concerned to ensure that women PhD students and PDRA/Fs are fully supported, informed and encouraged in their career development: see *Good Practice* and **ii.** below. The department is highly successful at supporting shorter-term PDRA/Fs into academic careers: 7 since 2008, including all 3 RAs funded by MacKay and Sklyanin's EPSRC grant, have gained permanent UK posts. A perfect example is Torrielli, who came to us from MIT and Utrecht. Supported in all the ways described above, in 2011 he became one of the founding staff of the new *Fields, Strings and Geometry* group at Surrey. Another, Vicedo, left Hamburg in the middle of a post-doc for a 1-year position at York; he too now has a permanent position. In Number Theory, Haynes came from Brandeis to York as a PDRA, and moved to Bristol as an EPSRC CAF. He is now returning, with 3 post-docs, to a permanent academic position at York.

Research leave and funding. Academic staff are supported with research leave, typically 1 term in 9, supplemented by a university-level teaching replacement scheme. A detailed research plan and post-sabbatical report are submitted, and leave is used strategically to develop research profiles or assist in developing large grant applications. In total, 63 such terms have been taken since 2008, including Nazarov's visit to the IHES, making possible his work with Khoroshkin and Vinberg published in *Adv.Math*., and Higuchi's visit to UC Santa Barbara, supported by a Royal Society

travel grant, to work with Marolf. Staff have a £500 annual travel funding allowance and a personal research account, giving them control over teaching buy-out, consultancy fees and 25% of grant indirect costs. Such funding has been used for visits, visitors, conferences, collaborations, and creatively to explore new interdisciplinary possibilities (for example, for archive visits to support MacKay's maths/history project). Staff are supported to attend and speak at conferences, including in term-time (facilitated by cover and replacement arrangements for teaching and pastoral duties). The department has a full tariff-based workload model to measure teaching and service (nominally 60% of colleagues' time, with 40% for research). All buyout from grant or other income is applied to reduce teaching and administration, so that (for example) a 20% buyout typically leads to a 1/3 reduction in teaching and admin.

International staff and visitors. 7 of the new academic staff referred to above were from overseas, including appointees from Hamburg, ETH Zurich and Sydney. In 2008-13 the department has hosted over 100 international academic visitors, typically in association with the collaborations listed in Sect. **e**. Examples include R.C.Vaughan FRS, and Fields medallist and Wolf prizewinner G. Margulis. Visits have been supported by both external schemes (*e.g.* RS International Exchanges) and university awards (*e.g.* York's Distinguished Visitors Fund).

Good Practice. The department has made excellent progress in employing female staff. In 2000 there were only 2 female permanent academic staff, while now there are 7, including 2 professors. Of the department's current 11 PDRA/Fs, 5 are women. The department was an early supporter of the LMS Good Practice Scheme (GPS) for Women in Mathematics. Its working group includes the Head of Department and Departmental Manager, representatives of all staff groups including PDRA/Fs, and PhD students. In 2012 the group conducted interviews with all staff, confirming a highly positive view of our organization, culture and working practices with respect to equalities, ethnicity and family/caring responsibilities. Issues were identified and changes made—for example, ensuring that Management Team and all committees' (non-personal) documents are freely available to all staff, and that representation on and access to these committees, to travel funds and to other resources is fully inclusive. A campus nursery offers 9am-6pm care, with full salary-sacrifice tax relief, and the department supports maternity, paternity, carers' and compassionate leave with detailed personal arrangements. All requests for Flexible Working Arrangements have been granted. The department is preparing an Athena Swan application, exploiting best practice through our joint appointments in Chemistry (AS Gold award) and Biology (Silver).

ii. Research students

Our aim is to make York an outstanding PhD choice, providing the support and encouragement which will enable our students to realize their ambitions. There are 10 applicants for every funded place, including many top-decile students from, for example, Cambridge (Pt3), ETH and other world-leading universities. All applicants are interviewed (in some cases by Skype). Our EPSRC DTG allocation doubled in 2013, and is now among the 12 highest nationally, and combines with CASE awards, internally-funded positions, overseas scholarships (*e.g.* from Pakistan, China and Libya), and self-funded students, alongside a large MSc/MRes cohort, to create a thriving graduate school. Recruitment in Statistics has improved greatly, with 3 overseas students joining in 2012. PhDs are advertised in the media and strongly through personal contacts and representation. Students take a range of advanced taught courses during their transition to independent research: we participate fully in the MAGIC consortium of teleconferenced graduate lectures, and run a 4-year PhD variant in which such material is integral. Research students are fully involved in their research groups' activities, and are encouraged to collaborate, both at York and with research partners elsewhere. With departmental support, they organise local and graduate seminars and larger meetings. They are encouraged to speak externally—at regional and national meetings, at graduate conferences and at seminars elsewhere. Participation at summer schools, both in the UK and abroad, is encouraged, and funded where possible. In the past four years our students have (co-)authored nearly 50 research papers, and *all* of our PhD students have completed within four years. Of the 36 students to have graduated in 2008-13, 22 have continued in academia or research. Destinations include an EPSRC PDRF, and post-docs at Oxford, Chicago, Aarhus, UBC and the *Heilbronn Institute*. Badziahin, a York PhD and PDRA in number theory, is now a lecturer at Durham; and various of our post-2008 PhDs have assistant-professorial posts worldwide.

In addition to regular documented supervisory meetings, each student has a Thesis Advisory Panel (TAP) consisting of the supervisor and two further academics. This monitors progress twice each year, with detailed reports and presentations from the student. The TAP mentors and advises on academic and career development (including teaching, summer schools and speaking opportunities, and post-doctoral and other employment) and skills training–the Department and University offer diverse training opportunities (currently over 80), including mathematics-specific induction programmes and training for teaching. TAP and supervision records are monitored by the departmental Graduate Schools Committee (GSC) and used to inform policy. Supervisory problems are rare, and are initially handled by the TAP, which reports to GSC for further action. Before thesis submission, students provide a portfolio containing evidence of skills training, and summarising progress in the four domains identified in the *Researcher Development Framework*. As part of our commitment to the LMS GPS (see above), we are seeking ways to increase our female PhD student numbers from the current 20%–for example, by inviting female PhD holders and other alumnae to speak as role models on open days and at the careers and alumni days at which we aim to inspire both graduate and undergraduate finishers with possibilities for their future.

d. Income, infrastructure and facilities

Infrastructure and facilities. The main department is housed in the newly (2010) refurbished James College nucleus, in keeping with the York vision of an integrated campus, and now has a strong visual identity. Interdisciplinary mathematics is partly hosted by YCCSA, which occupies the flagship building of the new Heslington East campus, the multi-award-winning £20M Ron Cooke Hub. A new wet laboratory has been created for fluid dynamics and mathematical biology, led by Bees. In the short term, departmental expansion will be accommodated through further development of and expansion into the James College nucleus. The department's research does not require extensive use of high performance computing. It has a 0.5FTE computing officer (Bostelmann) and its own Moodle-based virtual learning environment, used for teaching and research communication, together with a full range of mathematical software for research and teaching (Maple, Mathematica *etc*.). It has a 0.6FTE research secretary, who assists with grant applications and grant and conference administration. The university library provides a full range of electronic and physical resources, with an ample budget for mathematics.

Research income. Recent expansion has been largely funded through student numbers, and a 2014-20 goal is to build research funding similarly. The portfolio includes a £1.6M EPSRC programme grant for 6 number theory RAs, which builds on two previous EPSRC grants for RAs (Beresnevich and Velani). This is exemplary of the department's strategy, of building colleagues' grant successes through small and standard level, providing mentoring and support (including buy-out for time spent preparing applications) for gradual build-up to programme and comparable level. An examplar is Twarock's mathematical virology group, supported by a £700K *Leverhulme Trust* grant for 3 RAs and 4 PhDs, and a wide portfolio of other support (EPSRC, Wellcome). Recent funding sources for fellows include Hungary (Hartmann), Quebec (Marquette), Switzerland (Zeindler), & the EU (Marie Curie: Ushakova and Indelicato). Travel and visitors are supported by additional departmental funding. The department has also provided various short-term bridging contracts for staff between grants. The Research Committee pro-actively seeks out appropriate funding sources, encourages and facilitates applications (supported by university Research Priming Funds), provides model solutions, and convenes groups of colleagues with suitable combinations of interests for funding calls. Future plans include seeking fellowship and large-scale EU/ESF and EPSRC funding in Algebra and Quantum Information. All new staff are mentored through their first grant applications, and all applications are internally reviewed.

Consultancy has an academic coordinator, is supported by our Advisory Board, and is used strategically in association with CASE PhDs and MSc placements to further our research plans. An exemplar is Wilson, who has longstanding collaborations with Fera (worth around £8M), with *Molecular Dimensions* (licensed to use her software), *Astra Zeneca* (via consultancy and a CASE award) and *GlaxoSmithKline (GSK)*. Discussions are now under way to build on a recently established collaboration with bio-tech SME *Eluceda*. Initial results have been very successful and a proposal to continue with a project for *Proctor and Gamble* is being developed. Further examples include Colbeck with *ID Quantique*, Knight with *EDF* and *Shell UK*, and, in Mathematical Finance, Kang with *Lacima* and Zastawniak with *RiskMetrics*. See also Sect. **e** below and REF3a.

e. Collaboration or contribution to the discipline or research base

Scientific Output. Since 2008, currently-employed members of the department have over 300 peer-reviewed publications. Colleagues have a total of over 40000 citations on Google Scholar, around 17000 of them since 2008, and 60 publications each have over 100 citations.

Colloquia, seminars and study groups. The department has a thriving range of colloquia and seminars, including weekly seminars for all research groups, supplemented by internal seminars, graduate lectures, and study/reading groups–around 40 term-long examples of these since 2008. In 2011-12, the department hosted over 130 seminars. Recent speakers have included J-Q. Fan (Princeton), B. Green FRS, R. Weber, K. Moffatt FRS and M. Proctor FRS (Cambridge), S. Kou (Harvard), B. McLeod FRS, S. Lauritzen FRS, T. Lyons and D. Segal (Oxford), Y. Nesterenko, V. Stepanov (Moscow), R. Vaughan FRS (Penn State) and M. Atiyah OM (Edinburgh). The department has an annual research awayday of colloquium-style talks aimed at stimulating connections across the Department and beyond.

Conferences and Collaborations. Colleagues have given around 170 UK departmental seminars & colloquia, 90 talks at UK research meetings, and 200 talks at international conferences/workshops [examples *italicized*], and have active collaborations, made research visits, and/or given invited lectures in an enormous range of institutions [standard text]. International examples include:

Bate Auckland, RU Bochum, MPI Bonn, Canterbury NZ, *Kaikoura, Oberwolfach* **Bees** Arizona**,** *Aspen***,** Barcelona, Botswana, *Brussels,* Cape Town*, Grenoble, Majorca,* MIT*, Nice, San Antonio,* Stockholm **Beresnevich** Bielefeld, Brandeis, *Luminy*, *Minsk, Oberwolfach*, Penn State, Yale **Bostelmann** *Bucharest, Copenhagen*, Goettingen**,** *Leipzig, Rome, Vienna* **Brzezniak** Berlin, Bonn**,** Maryland, Paris 1, Pisa, Prague, Salzburg, Sydney, Warsaw **Busch** *Budapest, Cologne***,** *Gdansk***,** *Kuala Lumpur***,** *Munich*, Osnabrueck, Sydney, Tel Aviv, Turku **Colbeck** *Beijing, Bielefeld,* Calgary, CalTech*, Dallas, Singapore,* Waterloo, Zurich **Corrigan** Bogota, *Budapest, Chernogolovka*, *Florence,* IAS Princeton*,* Kyoto*, Landau Inst., Leiden, Moscow*, *Natal*, Sao Paulo, *Seoul*, *Tianjin* **Daletskii** Bielefeld, *Bonn, Caen, Kaiserslautern*, *Luxembourg*, Kiev **Delius** *Bielefeld, Bordeaux,* Copenhagen, Canterbury NZ, Madrid, Zurich **Donkin** Aachen, Athens, *Coimbra, Lausanne*, Rome **Everitt** *Tel Aviv***,** Columbia NY, Fribourg, Geneva, *Ilorin*, Nashville **Fewster** *HIM Bonn***,** C. Conn. State*, Frascati*, *Goettingen, Hamburg*, Leipzig, Miami*, Oberwolfach,* AEI Potsdam*, Regensburg*, Trento, Tufts, *Vienna*, Warsaw **Haynes** Aarhus, *CMI Harvard, Luminy,* KIAS (Seoul), *Oberwolfach,* Tel Aviv, ETH Zurich **Higuchi** Belem, AEI Potsdam, *CERN*, Sao Luis, *Sao Paulo*, *Perimeter Inst*., UC Santa Barbara **Hughes** Case Western R.**,** *Jeju, Oberwolfach, Uppsala, Zurich* **Kang** *Kyoto, Minneapolis, Lisbon, Prague,* Singapore, *Strasbourg, Sydney,* Tokyo,*Toronto* **Knight** Brussels, *San Diego, Paris* **Li** *Adelaide*, Chicago, *Istanbul*, LSE, Penn. State, *Singapore*, Sydney, Yale **MacKay** Gothenburg**,** Krakow*,* NPS Monterey (CA), *Prague* **Nazarov** *Banff***,** Bonn, IES Cargese, *Dubna*, Marseille**,** *Moscow*, *Oberwolfach*, IHES Paris, Rome, *Uppsala*, Weizmann Inst. **Rejzner** Goettingen, Lyon, *Madrid, Milan*, Paris VI & VII, Rome, *Stony Brook*, Trento, *Trieste*, Utrecht, *Vienna* **Twarock** *Arizona S., Fribourg***,** *Galveston,* Helsinki, *Krakow***,** *Lausanne***,** Leipzig**,** *Columbus* **(***Ohio), Nova Scotia,* Padua, Princeton, Riverside (CA) Rockefeller (NY), Tampa, *Trieste*, Turin, UC Los Angeles, *Ventura,* Washington (NIH) **Velani** Aarhus, *Banff*, *Boulder*, *Luminy*, Lyon, Minsk, NSF Arlington, *Oberwolfach*, Paris XII, Penn State, Strasbourg, Uppsala, *Vienna, Vilnius* **Vladimirov** Beijing**,** Hong Kong**,** *Moscow,* Novosibirsk**,** *St Petersburg*, Princeton **Weigert** *Besançon,* Beijing, Conceptión, *Cuernavaca,* Dijon, *Kuala Lumpur*, Singapore, *Stockholm, Tianjin, Traunkirchen* **Wilson** *NKI Amsterdam*, Barcelona, *Hamburg*, Helsinki, BH Singapore **Zastawniak** *AIMS Cape Town*, Hangzhou, Krakow, Nowy Sacz **Zhang** Princeton, Columbia, Wisconsin-Madison, Penn State, Adelaide, Taiwan, Singapore, Shanghai **Zorin** Caen, Minsk, Paris, Saint-Etienne, *Tossa del Mare*.

An exemplar is Busch and Colbeck's work with colleagues at Cambridge, ETH Zurich, Hannover, Oxford and elsewhere, with many publications in *Nature* journals and *Physical Review Letters*, and many presentations at leading conferences. This work has grown organically over 5 years, aided by regular mutual visits (including to *ID Quantique*), and supported by EPSRC, the EU, the Swiss National Science Foundation (NSF), the ERC and *Industry Canada*, amongst others. Another is Higuchi's longstanding Brazilian collaboration, supported by the ICTP and 3 Brazil CNPq grants, which led to a definitive 2008 review of the Unruh effect (with around 200 citations).

Conference highlights include: Bees' keynote talk at the 2011 Aspen *Ocean Symposium* on *Physical microenvironments modulating biological interactions in the ocean;* Busch's plenary lecture on *Dealing with Uncertainty* at *Quantum Optics,* Turku*,* 2009*;* Corrigan's plenary talk at the XXIX *International Colloquium on Group-Theoretical Methods in Physics* (GROUP29), Tianjin, China; Donkin's talk at *Algebraic Groups and Invariant Theory*, Ascona, 2009, alongside Serre, Kostant and Ginzburg; Fewster's talks at the *50th anniversary of Algebraic Quantum Field Theory* (Goettingen 2009), and the conference for Rudolf Haag's 90th birthday (Hamburg 2012); and Velani's talk at the Heilbronn Annual Conference (Bristol, 2010) and the conference for Wolfgang Schmidt's 80th birthday (Vienna, 2013). Twarock gave the 2011 *Plancherel Lecture* in Fribourg (Switzerland), and the 2012 *Ladyzhenskaya Lecture* in Leipzig.

Advice, Esteem and Service includes reviews for the NSFs of Canada, Chile, Czech R., France, Georgia, Germany, Hungary, Italy, Romania, Switzerland and USA, & reviews/panel membership for EPSRC, NERC, the Leverhulme Trust and the European Research Council. Highlights include Corrigan's Chairing of the 2012 Weyl Prize committee, the 2008 Royal Society (RS) SC 1, and a 2009 STFC committee to review the *Isaac Newton Institute* (INI); and membership of the RS *Leverhulme Trust* Senior Fellowships panel 2009-11, the RS URF panel Aiii 2013-, and the RAE2008 Applied Maths panel. Twarock is a member of the EPSRC Strategic Advisory Team for Math. Sci. and the INI Scientific Steering Committee. Zastawniak is a member of Norway's *eScience* panel. Sklyanin was elected FRS in 2008, and Busch to the *Académie Internationale de Philosophie des Sciences* in 2009. Velani was an invited member of the 2011 EPSRC strategic Pure Mathematics Workshop, and is a member of the LMS Research Meetings committee.

Editorial work. Associate Editors and Editorial Board members include Busch for *Foundations of Physics*, Gould for *Communications in Algebra* (and two other journals), Twarock for *Computational and Mathematical Methods in Medicine* and *Molecular-Based Mathematical Biology* and Zhang for the *Journal of the American Statistical Association.* MacKay and Velani are LMS Editorial Advisers. Busch is an Editor of the Springer book series on *Fundamental Theories of Physics*. Higuchi was a 2008 Outstanding Referee for the American Physical Society (publishers of *Physical Review* and *Physical Review Letters*). Twarock guest-edited two special issues on mathematical virology, for the *Journal of Computational and Mathematical Methods in Medicine* (2008 v9) and *Journal of Physical Biology* (2010 v7).

Organization of Research Meetings. Colleagues have helped to organize over 30 conferences and workshops, including a 6-month INI programme (Brzezniak). Bees was Chair of the Scientific Committee of the *International Conference on Applications of Fluid Dynamics* in 2012. Fewster co-chaired the parallel session on *Quantum Fields in Curved Spacetime* at the 20th *International Conference on General Relativity and Gravitation* (GR20) Warsaw, 2013. Meetings hosted by York include *ICFT2012*, *BritGrav 2008*, *Mathematical Modelling in Ecology and Evolution 2013,* eight series of LMS Scheme 3 meetings and the 2008 *British Mathematical Colloquium*.

Interdisciplinary research and industrial collaboration are facilitated by YCCSA, our joint appointments, and our departmental Advisory Board, whose members include the directors of Fera, the *Smith Institute* and (up to 2012) of the *Heilbronn Institute*, and senior staff from *Barclays Capital*, *BT Group* and the *Institute and Faculty of Actuaries*. The board provides advice, links and new directions across all our activities. For example, a 2013 colloquium between the Number Theory group and *BT Innovate & Design* explored the industrial potential of the group's research in signal processing. Industrial collaborators (see REF3a) include *AstraZeneca*, *Eluceda*, *GSK*, *Molecular Dimensions* (Wilson), *Lacima* (Kang), *EDF, ShellUK* (Knight), *Citration* (A. Wood), *RiskMetrics* (Zastawniak) and *IDQuantique* (Colbeck). Colleagues collaborate *e.g.* with chemists (Vladimirov, Wilson), biologists (Bees**,** Pitchford**,** Twarock**,** A. Wood), physicists (Busch, Colbeck), economists (Eveson) and historians (MacKay**,** A. Wood). Such research is supported by joint MSc programmes*,* enabling regular exchange of people and ideas with industrial partners. Recent examples include the *Mathematics in the Living Environment* MRes, in close cooperation (in projects and student placements) with CEFAS (on whose scientific board Pitchford sits), the *Food and Environment Research Agency* (Fera) and other bodies (see *Consultancy*, Sect. **d**). Twarock's virology work (see Sect. **b**), which brings together mathematicians, chemists and biologists, is exemplary: highlighted by *Global Medical Discovery*, the collaboration is now filing a patent (GB1315785.4, September 2013), and has the potential to revolutionise anti-viral therapies.