Graduate Study Opportunities in Applied Mathematics at Bristol

The School of Mathematics is one of the largest schools in the Faculty of Science at the University of Bristol with about 60 members of academic staff covering a range of Applied Mathematics, Pure Mathematics and Statistics research. It has an international reputation for research excellence in each of these areas, as was demonstrated by the UK government's Research Assessment Exercise in 2008 where our Applied Mathematics group was ranked third in the UK (by the grade-point-average ranking used in Times Higher Education, for example). There are currently 20 full time members of academic staff in Applied Mathematics, supported by 13 Postdoctoral Research Assistants and 27 Postgraduate Students.

The success of the Applied Mathematics group is based on attracting not only the best available staff, but also by recruiting the best possible Ph.D. students; it is often their work which is at the cutting edge of modern research. We therefore welcome applications to study for degrees at the level of Ph.D., M.Sc. by research, M.Res, and M.Sc. in Mathematical Sciences. A Centre for Complexity Sciences provides an additional 10-15 postgraduate places on an integrated multidisciplinary M.Res/Ph.D. programme in conjunction with Departments in Engineering Mathematics and Computer Science, and the Centre for Doctoral Training in Communications offers a four-year PhD programme in conjunction with the Departments of Electrical and Electronic Engineering and Computer Science. The School is also involved in the M.Sc. by research programmes in the Science of Natural Hazards (run by the Earth Sciences department)

The research interests in the group are wide and varied and broadly captured by the following themes:

Complex fluids	Discrete geometry
Dynamical systems	Granular flows
Laboratory experiments	Liquid crystals
Nanoscience	Material science
Quantum chaos	Quantum information+computation
Random matrices	Scientific computing
Turbulence	Waves
Complexity	Soft biological matter

This booklet is designed to provide detailed information on Postgraduate Study within the Applied Mathematics group. This information can also be found online at:

`http://www.maths.bris.ac.uk/study/admissions_postgrad/`

and by following the links to the Applied Mathematics research themes. For additional information and enquiries, contact:

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1 An Overview of Research in Applied Mathematics

Topics for postgraduate study in the Applied Mathematics group are usually from the areas listed below. Occasionally students come with specific projects in mind. It is not unusual for prospective students to have an interest in one or more of these areas and to seek guidance about specific project topics. A detailed list of possible research projects with each supervisor is included in the end of the booklet.

Dynamical Systems and Statistical Mechanics

Most physical problems can be viewed as a dynamical system. Typically this involves studying the solution structure of nonlinear equations, understanding how these solutions may vary as the dynamical system changes and discerning generic properties of the solutions, for example will they exhibit chaotic behaviour. There are connections to Quantum Chaos as well as to the Ergodic Theory and Dynamical Systems group in Pure Mathematics. The following people have interests in this area: Dr. Carl Dettmann, Dr. Roman Schubert, and Prof. Steve Wiggins. For further information see http://www.maths.bris.ac.uk/research/applied/themes/dynamical_systems/.

Quantum Chaos, Random Matrix Theory and Number Theory

Quantum mechanics, the theory of matter on small scales, plays a centrally important role in many of the most important areas of science and technology (e.g. lasers, mesoscopic and nanoscopic systems). However, few quantum systems can be solved analytically. For the rest, methods of approximation are required. Among these, asymptotic methods based on classical (Newtonian) mechanics are of increasing importance, especially in mesoscopic and nanoscopic systems, which lie at the boundary between the classical and quantum worlds. Within classical mechanics there is a broad spectrum of qualitatively different dynamics, ranging from integrable (completely regular) to strongly chaotic (highly irregular). Quantum Chaos is the area of research concerned with how this fact manifests itself in quantum mechanics. It is an exciting and rapidly developing field, encompassing the mathematical analysis of new quantum phenomena and a wide variety of applications in many areas of science and technology (e.g. in nanoscale systems and microlasers). There are deep connections with Random Matrix Theory – the study of the statistical distribution of the eigenvalues of matrices picked at random from some suitably defined ensemble – ergodic theory, and several areas of number theory, such as the theory of the Riemann zeta function and other related objects. Many fundamental developments in the subject have followed from work carried out here in Bristol. The following people have interests in this area: Dr. Carl Dettmann, Prof. Jon Keating, Dr. Francesco Mezzadri, Dr. Sebastian Müller, Dr. Jonathan Robbins, Dr. Roman Schubert , Dr. Martin Sieber, Dr. Nina Snaith and Dr. Yves Tourigny. There is a close relationship with the Dynamical Systems and Quantum Information groups and with the group in Physics led by Professor Sir Michael Berry FRS. There is also a close connection with the number theory and ergodic theory groups in Pure Mathematics.

Some examples of research in number theory, random matrix theory, and quantum chaos can be found online:

http://www.maths.bris.ac.uk/research/applied/themes/random_matrix/

http://www.maths.bris.ac.uk/research/applied/themes/quantum_chaos/

Fluid Dynamics

Fluid dynamics describes a tremendous variety of phenomena from the large scale (e.g. weather and ocean systems on Earth and other planets or stars) through medium scales (e.g. the flow around grand prix racing cars) to very small scale (e.g. microdroplets for drug delivery). Our main aim is to understand how the nonlinear character of the hydrodynamic equations leads to the wealth of flow properties observed. These can range from the formation of novel flow structures, in particular those covering many length scales, to fully turbulent flows. We are also pushing beyond the boundaries of classical hydrodynamics by studying polymeric fluids, granular media and flows on the nanoscale. This places our group at a junction between mathematics, physics, chemistry, engineering, and geophysics. Our in-house fluid dynamics laboratory keeps us closely connected to the "real world", and presents us with ever new theoretical challenges. The following people have interests in this area: Prof. Jens Eggers, Dr. Andrew Hogg, Prof. Rich Kerswell, and Dr. Richard Porter.

Traditional research into fluid dynamics at Bristol involves free surface flows, especially water waves (Dr. Richard Porter), and turbulence and transition to turbulence (Prof. Rich Kerswell). More recently, it expanded to include granular media and particle laden flows and complex fluids (Dr. Andrew Hogg, Prof. Rich Kerswell, Prof. Jens Eggers), and vortical flows (Prof. Rich Kerswell).
Further information about fluid dynamics group is provided by the web site

http://www.maths.bris.ac.uk/research/applied/themes/fluid_dynamics/

Quantum Computation and Quantum Information Theory

In the past five years the new subjects of quantum computation and quantum information theory have emerged which both offer the potential for immense practical computing power and also suggest deep links between the well-established disciplines of quantum theory and information theory and computation. On the one hand computer chips will soon be so small that we will have to grapple with the fact that electrons inside the processing elements become "smeared out", for example they can tunnel out of the wires: Heisenberg's Uncertainty Principle seems to be at odds with the desire for reliable computation. On the other hand it has been realised very recently that one might be able to take advantage of intrinsically quantum features to build quite new types of computers – quantum computers. We are only just beginning to understand what quantum information is and what quantum computers can do. We have close links with the physics and computer science departments and our group is interested in all aspects of Quantum Information Theory (foundations, nonlocality, entanglement, Quantum Shannon theory, Quantum computational models, and Quantum algorithms), and Experiment (Quantum Key Distribution, Single photon sources, Nonlocality experiments, "Natural computation").

The following people have interests in this area: Prof. Noah Linden, Prof. Andreas Winter and Dr Karoline Wiesner.

The quantum computation and quantum information theory group may advertise additional PhD and other positions on the web:

`http://www.maths.bris.ac.uk/QCIG/positions.html`

Numerical Methods

The mathematical modeling of nonlinear phenomena sometimes leads to differential equations that are too difficult to solve by known analytical methods. In such cases, numerical methods can provide much insight into the properties of the solution set. Two threads of research are represented in the group; one where the use of numerical techniques is motivated by particular applications, and another where the focus is on the theoretical study of the effectiveness of the numerical methods themselves. The following people have interests in this area: Prof. Rich Kerswell, Prof. Jens Eggers, Dr. Yves Tourigny. For further information see `http://www.maths.bris.ac.uk/research/applied/themes/scientific_computing/`.

Materials Science, PDEs, Variational Problems and Applications

Recent years have seen intense interaction between mathematics and materials science, including solid mechanics and liquid crystals. This has borne much fruit – in solid mechanics, the explanation of intriguing material behavior (e.g., the shape memory effects) by mathematical models that relate behavior to microstructure; in liquid crystals, models relating static and dynamic properties to the existence and regularity of harmonic maps, possibly with defects, between topologically nontrivial spaces. This successful interaction has in turn raised a number of questions, many of which are of interest simultaneously in mathematics, in the physical sciences and in engineering. The relevant mathematical areas are primarily, but not exclusively, calculus of variations, partial differential equations, functional and real analysis and topology. Specific research problems include the following. Solid mechanics: microstructure evolution in solids, homogenization of (polycrystalline) materials with degenerate energy, computation of quasiconvex hulls and morphology formation in biological tissues as a result of stresses induced by growth. Liquid crystals: topological classification, energy bounds, for nematics in polyhedral geometries with natural, e.g. tangent, boundary conditions; number of smooth solutions, regularity of weak solutions; switching mechanisms, applications to bistable display technology. The following people have interests in this area: Dr. Isaac Chenchiah, Dr. Tanniemola Liverpool, Dr. Jonathan Robbins, and Dr. Valeriy Slastikov. For further information see `http://www.maths.bris.ac.uk/research/applied/themes/material_science/`.

Nanomathematics

It has been stated that nanotechnology and nanoscience is in the process of giving rise to the second industrial revolution. The hope and promise is that nanotechnology and nanoscience will lead to the realization of many broad goals of society; such as an improved understanding of nature and an ability to control it, new manufacturing processes that increase productivity and are environmentally friendly, breakthroughs in healthcare and health treatments that are cheap and widely available, solutions to issues surrounding sustainable development, and, in general, extending the limits of human potential. Solely for nanotechnology and quantum information the University is building a new four story million building consisting of research and teaching laboratories, offices and seminar and discussion rooms, that is purpose designed to facilitate interdisciplinary collaboration. The building is specifically designed to enable collaboration and interchange of ideas between workers in Bristol and with collaborators in the UK, Europe, and the US. The University of Bristol currently has a critical mass of workers resulting in a vibrant and stimulating multidisciplinary research environment in nanotechnology and nanoscience. Workers across the University including in the schools of physics, mathematics, computer science, electrical engineering, biology, and chemistry are all currently contributing to this effort. Within the School of Mathematics we work within the following research themes which are fundamental for many aspects of nanotechnology:

- *Transport in nanostructures* – the driving force that makes many nanosystems "work".
- *Interaction of deterministic and stochastic dynamics across many differing time and length scales* – a central issue that has received little attention which is important for understanding, e.g., the control and manipulation of proteins and DNA.
- *Bridging length and time scales* – possibly the central problem of nanoscience involving a huge number of new modelling issues and considerations, e.g., important issues are the merging of continuum and molecular descriptions, and the merging of quantum and classical descriptions.
- *Self-assembly* – a key mechanism for manufacturing and fabrication at the nanoscale and an area where new modelling and predictive tools may lead to new technological breakthroughs.
- *Coherence and decoherence: the quantum/classical interface*
- *Quantum information theory*
- *Nanofluidics* – important for a variety of processing and fabrication techniques at the nanoscale.
- *Data visualization and software development* – the modern partner of theory and modelling, but requiring new approaches for dealing with massive data sets.

Each of these themes demands new techniques and approaches for theory, modelling, and simulation and our interdisciplinary program built around the unification of these ideas and approaches will lead to a new *nanomathematics*. Applied mathematics researchers involved are Prof. Jens Eggers, Prof. Jon Keating, Prof. Noah Linden, Prof Stephen Wiggins, Dr. Carl Dettmann, Dr. Martin Sieber, and Prof. Andreas Winter.

Complexity

The School of Mathematics is part of a major initiative to create a new Doctoral Training Centre, the Bristol Centre for Complexity Sciences. The Centre has been set up thanks to a successful £4 million bid to the EPSRC and the theoretical hub of the programme is a collaboration between the Applied Mathematics and Statistics groups in the Mathematics school together with the departments of Engineering Mathematics and Computer Science.

The Centre is recruiting 10-15 students a year to an integrated multidisciplinary research and training environment, linking mathematics, statistics and computer science with application areas in engineering, life and molecular sciences.

Within the Applied Mathematics group this initiative is led by Dr Karoline Wiesner together with Prof. Noah Linden, Prof. Jens Eggers, Prof. Jon Keating, Prof. Rich Kerswell, Prof. Stephen Wiggins, Prof. Andreas Winter, and Dr. Carl Dettmann, Dr. Martin Sieber.

For further information see http://bccs.bris.ac.uk/ and http://www.maths.bris.ac.uk/research/applied/themes/complex_systems/.

Collaborations and Research Groups

The Applied Mathematics group has many strong research links with the Pure and Statistics groups and in particular with other schools and faculties within the University. This is one of its strengths. Within Applied Mathematics, there are opportunities to interact with groups in Engineering Mathematics, Physics, Earth Sciences, Civil and Aerospace Engineering, Physical and Theoretical Chemistry and Computer Science and Biology.

The Centre for Environmental and Geophysical Flows brings together interested staff from the schools of Mathematics, Geology, and Geography. The objective of this Centre is to identify and develop connections between geophysical and industrially relevant problems in order to further the understanding of fluid motions within the environment. For example, an understanding of the flow of a hot viscous liquid over a cold surface is relevant to the hazard analysis of both magma flows from volcanoes and hypothetical containment breaches in nuclear reactors. The property of buoyancy reversal of a coignimbrite volcanic eruption cloud is also observed in accidental releases of highly toxic hydrogen fluoride into the atmosphere. Models to describe the dispersal of pollutants in water or in porous rock can be applied to modelling the movement of traffic on a motorway. The existing seminar series run by the Centre provides an excellent complement to the School's activities and is being followed up with coordinated computer and laboratory support.

The Laboratory for Advanced Computations in the Mathematical Sciences is a facility based around the 160-node Beowulf cluster (soon to be upgraded to the new High-Performance Computing facility), and provides computing resources to the school of mathematics and any University researcher who may need to run heavy-duty computational experiments. These are vital for exploring complex systems such as climate modelling, turbulence and nuclear explosions, for example.

Many staff members have research connections with industrial and government organisations. In particular the mathematical physics group have close research links with Hewlett-Packard Laboratories, both in Bristol and in Palo Alto.

Academic Staff in Applied Mathematics

Below is a list of academic staff and a summary of their main research interests.

Dr. I. V. Chenchiah: Mathematical problems in solid mechanics and materials science: Statics and dynamics of microstructures and phase transitions in solids; Growth of biological materials; Applications of non-convex calculus of variations and partial differential equations.

Dr. C. P. Dettmann: Classical and semiclassical dynamics including open dynamical systems, mathematical billiards, periodic orbit theory, and decay of correlations, with applications to nonequilibrium statistical mechanics and optical microresonators.
Prof. J. Eggers: hydrodynamics, complex fluids, and statistical mechanics; in particular phenomena involving many length scales and pattern formation.
Dr. A. J. Hogg: geophysical and environmental fluid dynamics; two phase flows, including suspensions, sedimentation and erosion; granular flows; experimental fluid dynamics.
Prof. J. P. Keating: quantum chaos, random matrix theory, and number theory.
Prof. R. R. Kerswell: geophysical and astrophysical fluid dynamics: magnetohydrodynamics, rotating fluid mechanics, hydrodynamic stability theory, numerical methods for partial differential equations.
Prof. N. Linden: quantum information theory and quantum computation; global/topological aspects of classical and quantum mechanics.
Dr T. Liverpool: Theoretical soft matter physics; Biological physics; Systems biology.
Dr. F. Mezzadri: applications of random matrix theory to quantum chaos, statistical mechanics and number theory.
Dr. S. Müller: quantum chaos and its relation to random-matrix theory; semiclassical methods in condensed-matter theory; disordered systems.
Dr. R. Porter: linearised wave theory in surface waves, acoustics, and elasticity; the interaction of waves with structures.
Dr. J. M. Robbins: liquid crystals and harmonic maps; quantum chaos; topology of integrable systems; the spin-statistics connection.
Dr. M. Rudnev: discrete geometry, arithmetic combinatorics, harmonic analysis.
Dr. R. Schubert: Wave propagation and dynamical systems; Quantum dynamics of chemical reactions.
Dr. M. Sieber: Semiclassical approximations in quantum systems; Quantum chaos and random matrix theory; Microlasers.
Dr. V. Slastikov: calculus of variations, pattern formation due to energy minimization; micromagnetics, liquid crystals.
Dr. N. Snaith: quantum chaos, in particular the connection between random matrix theory and number theoretical functions such as the Riemann zeta function.
Dr. Y. J. M. Tourigny: disordered systems, particularly the study of the energy levels of Schroedinger operators with a random potential. More generally, topics at the intersection of mathematical physics and probability theory.
Dr. K. Wiesner: quantum computational mechanics; complex systems.
Prof. S. Wiggins: dynamical systems and applications.
Prof. A. Winter: quantum information and quantum computation; discrete mathematics.

2 Degrees Available

2.1 PhD

The normal entry requirement for a PhD in Bristol is a good honours degree (1st class or upper second class) in Mathematics or a related subject from a British University; equivalent qualifications from overseas institutions are accepted. Funded positions are awarded on a competitive basis. The funded period of study is three and a half years. The UK Research Councils currently award research studentships for maximum three and a half years for British and EU students who have been residents in UK for 3 years prior to application.

Each student has an adviser with whom he or she works. In many cases the adviser is chosen before the student arrives. This is necessary for certain studentships. In other cases, the adviser is chosen in the first few weeks of study. Many students are also supervised jointly by two advisers.

Research degrees are awarded on the recommendation of the examiners of the student's final dissertation; this includes an oral examination.

New starting students are expected to attend postgraduate lecture courses, and sometimes undergraduate lecture courses, in order to ensure a solid background knowledge of their subject. Weekly seminars keep the School abreast of current developments and all students are expected to attend. 'Formal' seminars are given by distinguished visitors from elsewhere in Britain and abroad. 'Informal' seminars are usually given by people already in Bristol, including postgraduates themselves. There is also a postgraduate seminar for Mathematics in business and industry, a postgraduate seminar "Mathematical Physics and beyond", and the MINGLE conference where students from Bristol present their work to each other. These events are organised by postgraduates themselves.

Students are encouraged and supported financially to attend meetings and conferences relevant to their work. Normally students will be funded to attend at least one international conference during the tenure of their award, provided that they are presenting a talk about their work.

2.2 Masters Programmes

The School is offering several masters courses:

- The School offers a taught **M.Sc. programme in Mathematical Sciences**. During this one year course students will focus on an area at the forefront of research in Mathematics where they will be able to attend specialised lectures and perform their own research under the supervision of a member of staff. This course runs for a full year from October to September. Students choose under the guidance of a mentor a combination of taught units that are usually examined in April and early June. Students focus on their projects during the summer. For more information, please see `http://www.maths.bris.ac.uk/study/admissions_postgrad/mscmaths/`.

- The Bristol Centre for **Complexity Sciences** is recruiting 10-15 students a year to an integrated multidisciplinary research and training environment, linking mathematics, statistics and computer science with application areas in engineering, life and molecular sciences. This programme programme consists of a one-year Master of Research

(M.Res.) and a three-year Ph.D. The M.Res. component consists of lectures in areas such as nonlinear dynamics, control theory, and statistics, several research projects (two 10cp projects and one 40cp project) as well as seminars and workshops.

- There is a one-year interdisciplinary M.Res. programme in Science of **Natural Hazards**. For more information see `http://www.gly.bris.ac.uk/hazards/index.html`.
- In addition, it is possible to complete an **M.Sc. by research** in any of the research areas of the School. However we are currently not able to provide funding for students studying for this degree.

2.3 Application Procedure

If you are interested in pursuing your postgraduate study in the school you should complete an online application, see
`http://www.bristol.ac.uk/prospectus/postgraduate/2011/intro/apply.html`.
Please include in the application the full list of courses and marks from your university, English language certificates for overseas students, two references and the areas of research you are interested in. These documents can be uploaded on the website. Letters of reference can also be sent directly by the reference writers. PhD applicants should already have, or expect to be awarded, a first or upper second class degree in a relevant subject. Submitting an application is in no way a commitment to accepting a place.

When the application has been received, UK applicants for PhD positions will be invited to visit Bristol to meet relevant staff. Reasonable travel expenses will be reimbursed. For overseas applicants we will often conduct interviews by skype or phone. Most decisions about funding are made between February and April, but for UK applicants there is also a possibility to make early offers to outstanding applicants who apply earlier.

Once a student accepts an offer, admission is handled by the Faculty of Science. Evidence must be provided of financial support for fees and subsistence. For most UK students this is satisfied by the award of a studentship.

For all inquiries, please contact either the postgraduate coordinator (`briony.maitland@bristol.ac.uk`) or

Dr Sebastian Müller,
Applied Postgraduate Admissions Tutor,
School of Mathematics,
University Walk,
Bristol, BS8 1TW, UK.

Tel: +44 (0)117 3315250
Fax: +44 (0)117 9287999
Email: `sebastian.muller@bristol.ac.uk`

Closing Dates. Closing dates depend on the type of funding. For EPSRC Doctoral Training Accounts there is no fixed closing date. But since most decisions about funding are made in February, March and early April, we urge prospective candidates **to apply as early as possible** before or during this period. The deadline for the first round of the University of Bristol scholarships will be **6 January 2012**. For the four-year PhD studentships in Mathematics as mentioned in section 2.4 there is a closing date on **1 February 2012**.

Language requirement. Overseas students whose native language is not English are required to give evidence of their fluency in English. There are various ways in which this may be done, e.g. in many countries there are offices of the British Council where a test such as the IELTS may be taken leading to a report for the University. The University's normal minimum requirement is 6.5 on IELTS and 600 on TOEFL (old style), or 250 on TOEFL (computerised), or 100 on TOEFL (Internet-based). However, the faculty of Science offers a degree of flexibility for postgraduate students in Mathematics and will accept an IELTS score of 6.0 or a TOEFL score of 577 (233 computerised; 90 Internet-based).

2.4 Fees and Financial Support

The tuition fees for one year's full time postgraduate study for 2012/13 will be:

	PhD	Math Sc. MSc	Nat. Haz. MRes
UK and other European Union students	£3,825	£9,000	£5,950
Other overseas students	£14,900	£17,000	£17,000

Please note all 'home' (UK/EU) fees are provisional and will be confirmed in April/May 2012. Information about eligibility criteria for home tuition fees can be found at `http://www.bris.ac.uk/academicregistry/fees/class.html`. The University believes that overseas students without dependents require about £9,000 per year to live in Bristol. There are several types of financial support available:

For all students

- **Four-Year PhD Studentships in Mathematics.** The University of Bristol invites applications for up to five fully funded four-Year PhD studentships in Mathematics with a start date 1 October 2012. Each studentship includes an annual stipend at EPSRC rates, and covers the Universitys tuition fees for EU or overseas students. An integral part of these studentships is for the candidate to develop their teaching skills alongside their PhD research. To this end, the successful candidate will teach four hours per week in term time and assist in the examination process. Training and mentoring will be provided. Applicants are expected to hold a first or upper second class honours degree, or international equivalent, in Mathematics. There are no restrictions on nationality. The closing date for applications is 1 February 2012. Short-listed applicants will be interviewed in the week commencing 20 February 2012. Interviews of overseas applicants may be carried out via video-link (skype).

For home (UK/EU) students

- **DTAs.** Another common method of funding also comes directly from the School which receives partial funding from the EPSRC for students undertaking PhD degrees by research, known as Doctoral Training Accounts (DTAs). There are currently no EPSRC awards available for students undertaking the MSc by research. These EPSRC studentships, normally available for a maximum period of three and a half years, are awarded on a competitive basis across the School of Mathematics, to students with relevant degrees at the First Class or 2.i level, or equivalent.

For UK and EU students who have been residents in the UK for three years prior to application, an EPSRC studentship meets all the tuition fees and pays a maintenance allowance to the student. In 2010/11 the value of this allowance is £13,590 plus tuition fees. Supplements may be available for disabled students, mature students, students with dependents and for students with suitable postgraduate work experience. Other students from European Union countries may be eligible for fees-only grants from the EPSRC and awards from the EU.

- **Project-specific grants.** Some supervisors hold grants to pay postgraduate students working on a specific projects. These openings are advertised on `http://www.maths.bris.ac.uk/research/news`.

- **Complexity.** The funding for the students taking part in the complexity M.Res.+Ph.D. progamme (see section 2.2) is allocated separately.

- **PhD studentships in Communications.** An EPSRC/industry funded UK Centre for Doctoral Training in Communications was launched at the University of Bristol in 2011. It offers 4-year enhanced PhD studentships with a taught programme in year 1 followed by a 3-year specialised research project.

  The Centre is jointly operated by the Departments of Electrical and Electronic Engineering, Mathematics and Computer Science, all acknowledged as leaders in their field.

  The Centre will address diverse challenges ranging from theoretical to applied research. The first year provides training in the broad area of Communications. This will provide the skills necessary to enable you to undertake cutting-edge research in your PhD, including:

  Lecture courses in advanced communication engineering topics with a choice of units Group and individual project work Enterprise and Transferable skills training Engagement with industry to demonstrate the application and context of research A topic for the PhD will be selected from a wide range of options towards the end of the first year and will normally build on the first year's individual project. Students will be able to choose their PhD projects from a wide range of proposals, most of which will be collaborative with industry. The PhD programme will also include a wide range of workshops and short course in years 2-4, in specialist technical subjects and business skills.

  CDT students will become members of a close-knit cohort working with a team of multidisciplinary academics from engineering, mathematics and computer science as well as with mentors and technical specialists from UK industry. Our industrial partners will also provide access to and training with the latest technology.

  Due to funding restrictions, applications are welcomed from UK/EU students only who are enthusiastic and highly-motivated who possess, or will shortly obtain, at least an upper second class degree in Engineering, Computer Science, Mathematics, Physics or a related science discipline.

Successful applicants who are UK citizens will receive an enhanced EPSRC 4-year studentship covering living expenses and fees. EU citizens who have been resident in the UK for 3 years or more are also eligible for the full studentship. Fees only support is available for other EU citizens.

For further information on the Centre go to: `www.bris.ac.uk/cdt-communications` or email `cdt-communications@bristol.ac.uk`.

The closing date for these openings is 30 June 2012.

Overseas Students

Many overseas students are funded by their own governments. Details of other sources of support for students planning to study at Bristol are available at
`http://www.bris.ac.uk/studentfunding/overseas_pg/` and
`http://www.maths.bris.ac.uk/study/admissions_postgrad/funding/`.
Here is a list of some of the options: please check the deadlines carefully.

- **University of Bristol Overseas Postgraduate Research Scholarships.** Competitive scholarships to attract the best international students to Bristol. The application deadline for the first round will be 6 January 2012. There will be a second round in March.
- **The British Council.** Contact the British Council Office in your own country for details.
- **Commonwealth Scholarships.** Offered to citizens of Commonwealth countries. Apply to the Commonwealth Scholarship Agency in your own country for details.
- **Marshall Scholarships.** For young Americans wanting to study in the UK. These are extremely prestigious scholarships, and the University would typically provide matched funding.

3 Life in the Applied Group at Bristol

3.1 Postgraduate Training

Within each sub-group of the Applied Mathematics group there are seminar series attended by Staff, Research Assistants and Postgraduate students. These attract world class speakers leading in research from around the UK and beyond, as well as providing a platform for postgraduates to talk about their research within their group.

First year students will be obliged to attend a minimum number of taught courses during your first year of research. Our school is involved in several initiatives to provide taught courses for postgraduates students.

Of most relevance to students in the Applied group is our collaboration with the Mathematics Departments of Bath, Imperial, Oxford and Warwick to form the Taught Course Centre (TCC), funded by a grant from the EPSRC. (`http://tcc.maths.ox.ac.uk/`) The TCC offers about 25 lecture courses across Pure and Applied Mathematics. Courses are delivered using interactive audio-visual technology: lectured from one institution, they may be attended interactively in all. These courses will be given by leading experts across a broad range of research areas and are aimed at providing Postgraduate students an advanced level of tuition of a broad range of Applied Mathematics topics. Courses are assessed (the method varies from course to course), but there is no formal qualification or accreditation earned. TCC courses can also be attended without assessment, and students may wish to do this to expose themselves to additional material in their first or subsequent years. Courses may be drawn from the Complexity initiative (with Departments of Engineering Mathematics and Computer Science) (`http://bccs.bris.ac.uk/`) or any of our level 3 & level M lecture courses delivered within the school. Attending these taught courses is a vital means of learning high level material and maintaining academic breadth.

In the Applied group, students are normally expected to take 2 assessed taught courses in their first year. These may be from the TCC or other available courses — including perhaps suitable courses from our undergraduate course offerings — as agreed with the advisor and Director of Graduate Studies.

3.2 Tutorial, Problem Classes & Marking Work

Postgraduates usually have an opportunity to supplement their income by giving tutorials and marking undergraduate work, and these are useful transferable skills. The hourly rate for this work is usually £13.79 and for tutorials this will include prepartion time. As a guideline we recommend that students only work up to 6 hours per week. Typically students have been earning in the range of 1600 to 1700 per year tax-free (these amounts are not guaranteed, but are typical of what students have been earning in the year 2011). Overseas students would need to provide proof that they are allowed to work in the UK. For the four-year PhD studentships in Mathematics (see section 2.4) students will teach four hours per week as part of their contract.

3.3 Facilities for Applied Research at Bristol

Research students are accommodated according to their research groups and interests. All postgraduates are given desks and computers often in shared offices and located close to people within their research groups. Students are given basic training by the Computer Support Officers in how the computing network is set up and each student is given a web site. The School is equipped with a range of computational facilities and software. Apart from having PC's on desks which are connected on a campus-wide network, there are servers and dedicated workstations running Linux grouped together to form a Linux Farm. Currently the school also has access to a Beowulf Cluster of 160 processors which is maintained by one of the Computer Officers. The School will have soon an access to a new High-Performance Computing (HPC) facility, cluster of 2024-CPU IBM computers which will be one of the fastest supercomputers in the UK.

Postgraduates are encouraged to use mathematical packages such as Matlab, Maple and LaTeXas well as become well-versed in the Unix and Linux Operating systems. The University runs courses in Computer-related topics which Postgraduates are free to attend.

There are good library facilities for Applied Mathematics publications based mainly within the Engineering building of the University and the Physics Library. The Library services also provide online subscription to many of the leading journals.

3.4 Living in Bristol

Bristol is a thriving city of 400,000 people, which offers a mixture of the old and the new. It was founded in the Ninth Century, and historically was one of the most powerful cities in the country, due to its port and the business savvy of its merchants. Its wealth has left a legacy of beautiful streets and buildings, and a harbourside at the centre of the city that is now a centre for arts and entertainment. There are many reminders of the work of Isambard Kingdom Brunel, not least the spectacular Clifton Suspension Bridge and the SS Great Britain. Over the last century the city has transformed itself from a port to a centre for technology, playing a key role in the Concorde and Airbus projects and currently boasting about 400 micro-electronics companies. More details are available from the official tourist website `http://visitbristol.co.uk/`.

The city is well-known for its thriving arts scene, particularly urban artists such as Massive Attack, Tricky, Portishead and the infamous graffiti artist Banksy. Aardman Animations, creators of Wallace and Gromit, are based here. It is also has strong environmental credentials: it is home to the Soil Association and Sustrans (who organise the national cycle network, see `http://www.sustrans.org.uk/`), and the Environment Agency. There is a thriving grass-roots social and environmental movement, with plenty of independent shops selling organic and locally-produced food, and a local branch of the Slow Food movement. Sports fans are well catered for, with two league football clubs, a Premiership rugby side and a county cricket ground which regularly hosts one-day international matches.

The University is located at the heart of Bristol, within walking distance of most of the city's facilities, including the Central Library, the Cathedrals (Anglican and Catholic), Bristol Temple Meads railway station, the Bus Station, the museums, theatres, cinemas (mainstream and independents) and art galleries, concert halls and music venues, the main shopping streets and the shopping centres at Broadmead and Cabot Circus, restaurants and clubs at the Harbourside, open space at Brandon Park. A walk through the beautiful Georgian streets of Clifton takes you to the Suspension Bridge over the Avon Gorge, and if you cross you get to Leigh Woods and the deer park and manor house of Ashton Court.

From either of the two railway stations (Bristol Temple Meads or Bristol Parkway) it is under two hours to travel to central London (Paddington). Just outside the city, the international airport has direct connections to other UK cities, to continental Europe, and to the US. The cities of Bath Spa, Cardiff, and Exeter are nearby, and many areas of outstanding natural beauty are within a few hours drive: the Cotswolds, the Brecon Beacons, Exmoor and Dartmoor, and the New Forest.

Bristol is a wonderful place to live, and this is just a brief summary: you should come and visit!

Accommodation. It is usual for students to find accommodation within about two kilometres of the university. There are a number of modern, well-equipped halls of residence (of which Dean's Court, Unite House, Chantry Court and Woodland Court are the biggest) fully or partly allocated to graduate students. It is the students' responsibility to find their own accommodation, but the University's Accommodation Office provides assistance, and should be the first point of contact when booking a room in a postgraduate hall of residence.

There are also a limited number of places for graduate students at favourable rates if they are willing to be 'in charge' of student houses, or to be in similar positions of responsibility within undergraduate halls of residence. Extra help is given to students from abroad by the International Centre. More details are sent to students when they are accepted for courses or with the details of registration before they arrive. Further useful information is sent to international students. For more details see `http://www.bris.ac.uk/accom/`.

4 Ph.D. Research Project Descriptions

4.1 Isaac Chenchiah

I am interested in mathematical problems in solid mechanics and materials science, particularly those involving microstructure and phase transitions, and those arising in biological systems. Recent years have seen intense interaction between mathematics, solid mechanics, materials science and biology. This has borne much fruit and has raised many questions of simultaneous interest in mathematics, physics, biology and engineering. The relevant mathematical areas are primarily, but not exclusively, calculus of variations, partial differential equations and real analysis.

Motility and Forces in cells (joint with Tanniemola Liverpool)

Biological cells can sense forces applied on them and respond to these forces. Their ability to do so influences a wide variety of biological process/phenomena such as motility (ability to move), lineage specification and cell division. What makes them interesting from the point of view of materials science is the fact that they are 'active', continuously using stored chemical energy in order to perform mechanical work. Such active materials show novel mechanical properties not seen in non-biological materials such as concrete, plastic or metals.

This project will attempt to use tools from statistical physics and micro-mechanics to further our understanding of the mechanisms of force sensing and the processes through which force influences cell behaviour. The work would be primarily theoretical but will involve some computations and interaction with experimentalists.

1. Sackmann, E., Biophysics: How cells feel the force, Nature Physics, 6(6), 407-408 (2010).

2. Liverpool, T. B. and Marchetti, M. C.: Instabilities of isotropic solutions of active polar filaments, Physical Review Letters, 90, 138102 (2003).

Percolation in elastic media (joint with Tanniemola Liverpool)

Percolation theory is concerned with the behaviour of connected clusters in a graph. When the behaviour in question is a mechanical property (such as stiffness or elastic energy density) the theory also provides a model for a variety of physical and biological systems, such as polymer gels and growing soft tissue. In this context, the problem changes from being purely probabilistic to being both combinatorial and mechanical. It becomes particularly interesting when the mechanical elements which comprise the material are small and thus subject to thermal fluctuations.

Then, developing a theoretical description of these materials requires mastering a subtle interplay between probability, statistical mechanics and elasticity. As a result, not much is understood about how the macroscopic properties of such materials depend on the microscopic configurations—this will be the subject of this project.

1. Kesten, H., What is ... percolation?, Notices of the American Mathematical Society, 53(5), 572573 (2006).

2. Wyart, M., Nagel, S. R., and Witten, T. A.: Geometric origin of excess low-frequency vibrational modes in weakly-connected amorphous solids, Europhys. Lett., 72(3), 486-492 (2005).

Phase transitions in Bacteriophage T4 (joint with Valeriy Slastikov)

Bacteriophage T4 is a virus that attacks bacteria by a fascinating mechanism which involves a phase transition in its tail sheath. The structure of this tail sheath and the mechanics of the phase transition are both important examples of wider themes that arise in the study of molecular biological systems such as DNA and viruses.

The structure of the tail sheath is very well understood. The goal of this PhD project will be to use this as a starting point to rigourously deduce its dynamic behaviour, including a description of the phase transition.

1. Animation at `http://www.seyet.com/bacteriophage-t4`.

2. Wayne Falk, W. and James, R. D.: Elasticity theory for self-assembled protein lattices with application to the martensitic phase transition in bacteriophage T4 tail sheath, Physical Review E 73, 011917 (2006)

Cooperative behaviour in multi-phase materials

When multiple phases coexist in a solid (usually as result of a solid-solid phase transition) the behaviour of the solid as a whole is strongly influenced, even determined, by cooperative effects between these phases. Such cooperative behaviour is typically not easy to study and the development of mathematical tools to do so has been a major theme of mathematical materials science in recent years.

There are several possible PhD projects in this broad area which I will be happy to discuss with interested applicants.

1. Isaac V. Chenchiah, Kaushik Bhattacharya, The relaxation of two-well energies with possibly unequal moduli, Archive for Rational Mechanics and Analysis, 187(3), 409-479, 2008

2. Isaac V. Chenchiah, Kaushik Bhattacharya, Examples of nonlinear homogenization in plane strain involving degenerate energies. I. Plane strain, Proceedings of the Royal Society A, 461(2063), 3681 - 3703, 2005

3. Carl-Friedrich Kreiner, Johannes Zimmer, Isaac V. Chenchiah, Towards the efficient computation of effective properties of microstructured materials, Comptes Rendus Mecanique, 332(3), 169 - 174, 2004

4.2 Carl Dettmann

I am happy to supervise well motivated students who want to work on mathematical physics and/or nonlinear dynamics. Two areas of particular interest are:

1. Open dynamical systems: What happens if you put a hole or two in a regular or chaotic dynamical system and let trajectories leak out? We can learn a lot about the dynamics, how to control it, and how trajectories get transported between systems connected by holes, by studying the distribution of escape times (where the trajectory is originally inside the system) and recurrence times (where it is initially injected through a hole). A good class of open systems to visualise are mathematical billiards of different shapes, where the holes are "pockets", typically located at the boundaries.

2. Wireless communication networks: What happens if you place communication devices ("nodes") randomly, and ask if they can all communicate with each other, given a (typically probabilistic) rule for whether any pair can connect? How does this depend on the shape of the domain? How can you use this information to design reliable networks? This project involves collaboration with Toshiba research labs in Bristol.

For more ideas, please look at recent publications available from `http://www.maths.bris.ac.uk/macpd/Publications.html`. They are research articles, hence rather technical; please read only to get the general idea, and then contact me to discuss your interests.

4.3 Jens Eggers

Formation and stability of Taylor cones

When a drop of dielectric fluid is placed in an electric field, it first extends along field lines. With slowly increasing field strength the resulting series of stationary shapes becomes unstable at a critical field, and evolves dynamically toward a new shape with sharply tipped cones at its end. This shape is strongly reminiscent of a stationary solution originally found by G. I. Taylor, representing a balance of surface tension and electric forces. Often, these cones are unstable at the tip, and a tiny jet is ejected from it. These so-called "electric jets" represent one of the most important methods to inject tiny droplets into a gas phase. The object of this thesis is to focus on the dynamics of the formation of the Taylor cone. Preliminary numerical calculations indicate that the dynamical structure that develops after the drop becomes unstable is a cone with an angle different from Taylor's prediction. Equally unexplored and perhaps related is the mechanism leading to the instability of the tip.

A fascinating aspect of the Taylor cone solution is that a variety of very similar structures are observed for example when a drop is placed in a strong shear flow, in the so-called "selective withdrawal" experiment, or in viscous drops running down an inclined plane. The first stage always consists of the formation of a singular, tip-shaped structure on the free surface. However, upon increasing the driving, this structure typically turns unstable to eject a jet. A second aim of this thesis is thus to identify common features in these diverse situations, and to draw conclusions about possible universal mechanisms of instability.

Drop impact

When a drop of water impacts on a smooth surface, it first flattens out to a thin "pancake" structure, which then retracts and rebounds from the surface. For all applications whose object is to deposit material on the surface, this typical behavior is of course extremely undesirable. The object of this thesis is to quantitatively describe the phenomenon of impact by developing simplified model equations for both phases of spreading and retraction. All previous descriptions were based on global balances, without paying attention to the actual drop shapes. However, there are a number of characteristic features of drop impact that need to be explained more quantitatively.

1. The above-mentioned "pancake" is in reality far from uniform, but ultimately an extremely thin film forms, bordered by a thick rim.

2. In retraction, low-viscosity liquids form a series of sharp steps, somewhat reminiscent of hydraulic jumps. If the liquid freezes during recoil owing to heat transmitted to the substrate (for example in the case of liquid solder), some of these features are strikingly preserved.

Most importantly, the actual droplet shapes as well as the flow field come into play when calculating the viscous dissipation during impact, which can no longer be neglected for higher viscosities. An even more dramatic effect is produced by the presence of tiny amounts of polymer additives: while the initial spreading is virtually unaffected, the recoil is strongly suppressed and the liquid is deposited even when its base viscosity is very small. While this effect is subject of several recent papers and patents for the agricultural industry (think of pesticides being deposited on plant leaves), it is not understood. Again, only the flow field will tell us about the stretching of the high molecular weight polymer, and where it eventually ends up. Further interesting and poorly explored subjects include the influence of solid surface properties and of the contact line motion.

The student would join a group of researchers actively investigating related topics.

4.4 Andrew Hogg

Projects are available with application to a range of particulate flows, including suspended sediment transport, dense granular flows and rapid avalanches. Particular attention is given to environmentally relevant processes and phenomena and research projects may employ analytical, numerical and experimental techniques. There follows a list of some focused projects, but many other topics could be investigated as well.

Granular segregation

Mixtures of particle with different sizes and densities tend not to remain uniformly mixed when flowing. For example, in an agitated mixture of particles, the smaller ones tend to migrate towards the bottom, a phenomenon that is common in the kitchen, but which causes problems in industrial processing and which plays a major role in determining the deposit from large-scale flows of particles in the environment. However despite its inevitability, quantitative models of segregation remain in their infancy and we cannot predict the rate of segregation of a mixture of particle sizes with any certainty. This project would address this issue by developing new models to capture recent experimental measurements of granular segregation, by developing simulations of the process in particular flows and by calculating the deposit that would be left behind by such motions.

Volanic ash flows in the atmosphere

Flows of volcanic ash are driven by the presence of suspended particles, which render the suspension denser than the surrounding fluid and this buoyancy difference drives the dispersion of the particle-laden cloud. The particles, however, continually settle out of the suspension, thus progressively reducing the excess density of the cloud and the speed of the flow. Volcanic ash clouds are also affected by atmospheric conditions and wind plays a major role in their dispersion.

The 2010 eruption of Eyjafjallajkull were a sequence of volcanic events at Eyjafjll in Iceland which, although relatively small for volcanic eruptions, caused very substantial disruption to air travel across western and northern Europe. The inability to predict the motion of the ash cloud with any accuracy became clear during this period; current models do not properly account for the motion of cloud through the atmosphere and its interaction with wind. These deficiencies will be addressed by this research to model the rise of the ash-laden volcanic plume through the atmosphere and its mixing with it, and the intrusion of the volcanic cloud through the atmosphere and its dispersion by the wind. The work could entail mathematical modelling, computation or laboratory experimentation on small-scale flows that share many features with these important environmental phenomena.

Suspended sediment transport

River currents and coastal waves may pick up sedimentary particles if their velocity is sufficiently high. Thereafter the particles are carried along in suspension with their submerged weight being supported by the action of fluid turbulence. It is important to be able to predict the quantity of sediment that a flow may transport so that accurate assessment may be made of the rates of coastal erosion or the effects of building new engineering structures such as barrages and harbours on the surrounding environment. The current formulae for predicting this erosion are highly inaccurate and estimates may be incorrect by orders of magnitude. This Ph.D. project will adopt a new approach to modelling suspended sediment transport. It will employ recent ideas from studies of turbulent fluid flows in which coherent eddies and other flow structures have been identified. These structures are potent means for transporting sediment in suspension and this project will examine how models involving these flows may significantly improve our understanding and ability to quantify the amount of particulate material that may be transported

Mud and debris flows

When a fluid is highly laden with particles or contains a significant fraction of mud, it may exhibit dynamical features that differ strongly from situations where the particulate phase is dilute. Most notably the fluid may exhibit a yield strength that must be overcome for motion to occur. This poses a significant control on the flows: in particular they may arrest or form channelised and braided streams. Recent experiments and field observations have highlighted a number of these features and Ph.D. projects in this area would develop quantitative, mathematical models of these effects.

4.5 Jonathan Keating

Project areas

Projects are available in the following areas.

1. Quantum chaos (the quantum properties of systems in which the classical dynamics is chaotic).
2. Random matrix theory (properties of matrices whose elements are random variables), including applications to complex wave problems, the Riemann zeta function and families of L-functions, and quantum information theory.
3. Semiclassical asymptotics (asymptotics of wave theories in the limit as the wavelength tends to zero; eg quantum asymptotics in the limit of small de Broglie wavelength).
4. Cosmological chaos.
5. See Jonathan Robbins' entry for a jointly supervised project on exotic states for quantum graphs.

Students interested in any of these areas can contact Professor Keating `j.p.keating@bristol.ac.uk` for related references.

There are close links with research interests of Dr C. P. Dettmann, Dr J. Marklof, Dr F. Mezzadri, Dr N. C. Snaith, Dr M. Sieber.

4.6 Rich Kerswell

I am generally interested in supervising projects in the following areas

1. Transition to turbulence and the state of turbulence itself in fluid flows using Dynamical Systems ideas (e.g. Nonlinearity 18 R17 2005, Phys. Rev. Lett. 105 p154502 2010 and http://arxiv.org/abs/1109.2459v1). Of particular interest now is uncovering localised flow solutions and understanding how they relate to turbulent spots and spatiotemporal behaviour seen in large flow systems.

2. Nonlinear dynamics of fluid flows generally (stability, bifurcation, nonlinear solution continuation and making links with direct numerical simulation of the Navier-Stokes equations e.g. J. Fluid Mech. 508 p333 2004 and for an example of non-uniqueness see J. Fluid Mech. 682 p132 2011. A lot of novel and powerful techniques have recently been developed in Newtonian flows which can be carried over to complex fluids. In polymer solutions, for example, a new type of 'elasto'-turbulence can occur which is awaiting theoretical treatment.

3. The dynamics of dense granular flows (e.g. J. Fluid Mech. 538, p399 2005, Phys. Fluids 17 057101, 2005, Phys. Rev. Lett. 102 p108305 2009). A recently proposed 'granular' rheology has raised the possibility of successfully modelling dense flows but needs to be further tested and developed to handle practical (industrial) flows such as silo flow (or, on a smaller scale, the traditional sand-filled egg-timer). There is opportunity here to marry experiments, theory and numerical computations (using discrete element methods).

Students interested in any of these areas can contact Professor Rich Kerswell R.R.Kerswell@bris.ac.uk for further information. Possible PhD projects are constantly evolving as the state of the art improves.

4.7 Noah Linden

My research is in the new field of Quantum Information which is one of the most exciting and dynamics areas science and technology. It is an interdisciplinary subject where mathematicians, physicists and computer scientists have made major contributions. Deep links have been forged between the previously unrelated disciplines of quantum physics and computer science/information theory. On the one hand there have been insights into fundamental issues in physics. On the other, totally new methods of computation, communication and information processing have emerged. Quantum information is concerned both with the fundamental science of quantum systems and with how one can use quantum resources to perform computational and other information processing tasks.

Despite a major international research effort, we are still at a very early stage in developing our understanding of this field. Many deep questions remain about the nature of quantum information and the possible scope of quantum systems for information processing tasks. Quantum information theory is also forcing us to ask new questions in fundamental physics.

My current research in is a number of different theoretical aspects of quantum information and quantum computation. These include the theory of entanglement and non-locality, quantum communication and foundational questions in quantum computation [such as what gives quantum computation its power]. Ideas from quantum information theory have also allowed us to make exciting progress in fundamental questions in statistical mechanics, and this is a further area that I have become interested in recently.

My recent papers can be found via `http://www.maths.bris.ac.uk/~manl/` These give an idea about what issues particularly interest me at present, and areas in which I would be interested in taking on PhD students.

4.8 Tanniemola Liverpool

My research involves mathematical models for soft materials also called complex fluids and biological physics.

Research on soft materials involves, (but is not restricted to) the study of emulsions, gels, foams, colloids, synthetic and bio-polymer melts and solutions, liquid crystals and other such systems. They are characterised by geometric structures on a mesoscopic scale several orders of magnitude bigger than the molecular scale but well below the macroscopic (human) scale.

Over the last few decades, we have come to realise that by understanding this structure (which can be described using simple geometrical models with a small number of physical parameters) it is possible to come up with a set of general principles, to understand many features of their macroscopic behaviour. It turns out that many microscopic details like detailed chemical structure can simply be used to determine the specific values of the physical parameters of the coarse-grained mesoscopic models. Of course this is not the whole story, a current active area of research is the study of soft systems to find out exactly those macroscopic properties cannot be separated from the microscopic details.

The separation of this mesoscopic scale from the macroscopic allows one to use the powerful techniques of statistical mechanics. The study of complex fluids is an interdisciplinary field with many fruitful interactions between physicists, chemists, and engineers and mathematicians.

The sub-cellular world has many components in common with soft condensed matter systems (polymers, amphiphilic molecules, colloids, and liquid crystals). But (and this is what makes it so fascinating) it has novel properties which are not present in traditional complex fluids. These new features include a number of specific interacting elements present that are crucial for biological function. The addition of these elements which can be both active and passive, lead to a highly non-equilibrium system with a rich spectrum of behaviours. A new generation of experiments using physical probes are giving us an unprecedented view of this non-equilibrium system at work. The search is on for an as yet undiscovered hierarchy of organisational principles which will enable us to understand these exceedingly complex systems!

I have several possible PhD projects that span these topics involving theoretical research but with close links to experiments.

See Issac Chenchiah's entry for two jointly supervised projects.

4.9 Francesco Mezzadri

Asymptotic properties of spectra and eigenfunctions of quantum chaotic systems

The central problem is to understand how the chaotic nature of the underlying motion of classical systems affects the corresponding quantum mechanics. The main theoretical questions concern the behaviour of the eigenfunctions and eigenvalues in the semiclassical limit, that is as Planck's constant tends to zero. In particular, it is believed that in the semiclassical limit the energy levels of generic chaotic systems are correlated like the eigenvalues of large random Hermitian matrices. This is known as the Random Matrix Theory conjecture. The models used to study these problems will be quantum systems whose time evolution is discrete; these are known as quantum maps.

Random matrix theory and critical phenomena in spin models

Recent studies have shown that random matrix theory can give new insight into the understanding of phase transitions in lattice systems. The problems to address include the behaviour of entanglement in the ground state of quantum spin chains, the study of universality of critical exponents and of the scaling hypothesis in two dimensional spin models. Thermodynamics variables in proximity of critical temperatures obey power laws whose exponents seem to depend only on the dimensionality and symmetries of the system; the scaling hypothesis, instead, asserts that the thermodynamic properties of a macroscopic system depend only on few relevant variables that characterize its behaviour on a particular time or length scale.

Correlations at the edge of the spectrum of non-Hermitian random matrices

The spectral correlations at the edge of the spectrum of random matrices with real spectra is well understood by the theory developed in the early '90s by Tracy and Widom. Their theory, however, does not apply to matrix ensembles with complex spectra. The main problem consists in computing the asymptotics of the kernel of the measure. Such kernel is usually a sum of orthogonal polynomials defined in the complex plane. The main goal is to develop suitable asymptotics techniques to compute such kernels. This would give us the tools to determine the correlations at the edge of the spectrum of ensembles of matrices with complex and quaternionic elements.

Distributions of zeros of derivatives of characteristic polynomials of random matrices from the classical compact groups

The behaviour of the zeros of the Riemann zeta function and other L-functions is affected by the properties of the zeros of their derivatives. The distributions of the zeros of derivatives of characteristic polynomials of random matrices are good models for the distributions of the zeros of derivatives of L-functions. Up to now the only distribution known is when the matrices are from the unitary group equipped with Haar measure, and only in certain asymptotic regimes. The purpose of this project is to improve previous results by computing higher order terms in the asymptotic expansion and extend them to the other classical compact groups.

4.10 Sebastian Müller

My principal research interests are:

- **Quantum chaos and its relation to random matrix theory:** In quantum chaos one considers systems whose classical motion is chaotic, i.e., depends sensitively on the initial conditions. One then investigates the quantum mechanical properties of these systems, for example their energy levels. It turns out that their are deep connections between the classical and quantum mechanical behaviour. Many aspects of this quantum behaviour are universal and and independent of peculiarities of the system. For example, the statistics of energy levels becomes universal, and the different energy levels of a chaotic system always have a tendency to repel each other. These universal properties agree with phenomenological predictions from random matrix theory.

  A central topic of my research is to understand the reasons (and, importantly, the conditions and limitations) of this universality. This can be studied using semiclassical approximations, i.e., by relating quantum properties of chaotic systems to their classical trajectories (in particular the periodic ones). It turns out that pairs of very similar trajectories are of crucial importance. This includes pairs identified by my Bristol colleague Martin Sieber as well as Klaus Richter; here one trajectory includes a self-crossing with a small angle and the second trajectory narrowly avoids the crossing but otherwise closely follows the first trajectory. Ultimately the importance of such pairs of trajectories is due to interference effects. More generally interference effects arise between trajectories that differ in arbitrarily many so-called "encounters" where an arbitrarily many parts of the trajectories come close. Correlation functions describing spectral statistics can be evaluated by by summing pairs of similar trajectories. These sums can be shown to give contributions in agreement with random matrix theory, and in recent work the connection between the semiclassical approach and the mathematical structure of random matrix theory has become closer and closer.

  Reference: S. Müller and M. Sieber, *Quantum Chaos and Quantum Graphs*, The Oxford Handbook of Random Matrix Theory, eds. G. Akemann, J. Baik, and P. Di Francesco (2011), `http://www.maths.bris.ac.uk/~maxsm/Chapter33.pdf`

- **Semiclassical methods in condensed-matter theory:** Methods developed in quantum chaos have important applications in condensed-matter theory. For example they can be used to show that the conductance of mesoscopic cavities becomes universal if the classical motion inside these cavities is chaotic. They also give interesting predictions for properties of normal conductors that are coupled to superconductors. Other research interests in this direction include the behaviour of many-particle systems, Bose-Einstein condensation, and Anderson localisation.

  Reference: S. Müller, S. Heusler, P. Braun, and F. Haake, *Semiclassical Approach to Chaotic Quantum Transport*, New J. Phys. 9, 12 (2007) `http://arxiv.org/abs/cond-mat/0610560`

- I am also interested in the theory of **disordered systems**, for example in the context of wireless communication.

I am happy to supervise PhD projects in these areas. Possible topics evolve continuously as the state of the art improves. They can range from more mathematical problems (using random-matrix theory, representation theory, or combinatorics) to condensed-matter physics. Two possible projects are listed below. Please do not hesitate to contact me if you are interested or have further questions (email: `sebastian.muller@bristol.ac.uk`). My recent publications can be found under `http://www.maths.bris.ac.uk/people/faculty/maxsm/`.

Anderson localisation in chaotic wires

The conductance of a wire is strongly reduced if the wire contains irregularities. This effect is well understood if the irregularity is due to disorder inside the wire; it is an example for a phenomenon called Anderson localisation. However the conductance is also suppressed if the wire is completely clean and just the shape of the boundary is irregular, leading to chaotic classical motion. In this project the behaviour of clean chaotic wires will be studied using semiclassical techniques. The conductance is a quantum mechanical property but in the semiclassical limit it can be expressed through interference effects between pairs of classical trajectories. One has to pay attention to fully capture the properties of the classical dynamics. In contrast to small conducting cavities one has to take into account effects due to the long length of the wire. It is expected that this dynamics over large distances can by modelled by a diffusion equation but there are also situations where the long distance dynamics will be different (displaying so called Levy flights). This project will study in detail the interplay between different types of classical dynamics and their signatures in quantum mechanics. The results could also be extended to spectral and wavefunction statistics.

Entanglement in mesoscopic conductors

A possible PhD topic would be to explore entanglement in mesoscopic conductors using the semiclassical techniques mentioned above. Entanglement is one of the fundamental features of quantum mechanics. For example a state of a two-particle system may be of the form $|a_1\rangle \otimes |a_2\rangle + |b_1\rangle \otimes |b_2\rangle$ where $|a_1\rangle, |b_1\rangle$ are possible states of the first particle and $|a_2\rangle, |b_2\rangle$ are possible states of the second particle. For such entangled states, measurements of one particle also affect the other one; if e.g. the first particle is found in state $|a_1\rangle$ the second must be on state $|a_2\rangle$. It has recently been proposed that entanglement could be observed in conducting cavities with multiple openings. One then has to consider a two-particle system involving an electron and a hole. Electrons that leave the cavity through one opening are associated to $|a_1\rangle$ while those leaving through the other one are in state $|b_1\rangle$. Similarly holes are either in state $|a_2\rangle$ or $|b_2\rangle$ depending on the opening through which they are leaving the cavity. Correlation functions between currents of electrons and holes leaving the cavity through different openings can now serve as an indicator for entanglement. A goal would be to evaluate these correlation functions using semiclassical methods.

These projects have close connections to the research interests of Prof. J. Keating and Dr. M. Sieber, and in the second case also to research in the Quantum Computation and Information group.

4.11 Richard Porter

I am interested in the use of analytical techniques to solve equations which are derived from studying the interaction of waves with structures in the context of water waves, acoustics, electromagnetic and optics, quantum theory and elasticity.

The interaction of waves with long obstacles and large arrays

There are many physical applications where one wishes to assess the diffraction of waves by structures which are very long compared to the wavelength of the incoming wave. Similarly, wave scattering by very large periodic arrays of scatterers is also an active area of research especially in the field of photonic crystals.

Typically, if a scattering array or obstacle is of infinite extent, the solution process is simplified. Conversely, if the scattering array or obstacle is small, then analytical/numerical methods solve the problem efficiently. (Think of Fourier Transforms and Fourier Series as being methods for representing a function over an infinite or finite region.) However, for large but finite structures or structures of semi-infinite extent the solution process is either prohibitively expensive to compute, or worse: the problem description itself needs to be completely respecified.

New methods for dealing with such problems have emerged in the last 5 years and this project will aim to develop those ideas further. Problems of ocean waves long over ridges, guided waves along long impedance surfaces and scattering of vibrational waves by arrays of pins in thin elastic plates semi-infinite arrays will be considered. The ultimate goal will be to develop methods to look at the so-called and as yet unsolved "quarter-plane" problem.

Integral equation techniques for wave scattering problems

Classical methods for scattering of waves by obstactles involves expressing the solution as a boundary integral over a surface whose integrand involves a function of the wave-field defined on the surface. This function is itself determined as a solution of a so-called integral equation. This integral equation is then often solved numerically but nearly always contains "singularities" which makes the numerical solution process tricky. This project aims to extend a method developed to overcome this difficulty of singularities in the numerical method for a class of water wave problems into other application areas. In particular, we shall look at how to implement this method in acoustics and electromagnetics and use it to considering numerical solutions to "high frequency scattering" by obstacles.

Wave energy

A current interest of mine is in developing new ideas for extracting energy from ocean waves. A current PhD student is working on this, but there may be some scope for extending these ideas to form the basis of a new project.

4.12 Jonathan Robbins

Liquid Crystals

a) Nematics in polyhedral geometries

Liquid crystals provide a variety of mathematical problems of both theoretical and practical interest. Our research concerns liquid crystals in polyhedral geometries, and combines elements of topology, partial differential equations, calculus of variations and harmonic maps. It has also been motivated by collaborations with researchers in the Digital Media Department at Hewlett-Packard Laboratories, Bristol.

Nematic liquid crystals are composed of rod-like molecules which are orientationally ordered but spatially disordered. The preferred orientation of the rods may be described by a unit-vector field (or, more precisely, a director field) which is a local minimiser of a certain energy functional. The associated Euler-Lagrange equations are nonlinear elliptic PDE's. Solutions are examples of harmonic maps between Riemannian manifolds.

In polyhedral geometries, liquid crystals often satisfy (approximately) tangential boundary conditions; on the faces, the director lies in the plane of the face, but is otherwise unconstrained. The boundary conditions produce a rich family of topologically distinct configurations. Our programme involves classifying these topologies and calculating, both analytically and numerically, the minimising configurations and their energies. Applications include bistable displays, in which the pixel geometry supports multiple energetically stable solutions which are topologically and optically distinct.

Topics for PhD research include i) existence and regularity of local minimisers of given homotopy type, ii) dynamics of configurations under applied fields and noise, including the creation and dynamics of surface and edge defects. The research would suit students with a broad range of interests in mathematics and mathematical physics. There is ample scope for numerical computations, too.

b) Onsager model for phase transitions in biaxial liquid crystals (with VV Slastikov)

Biaxial liquid crystals can exhibit a richer variety of phases than do nematics. Their constituents may be regarded as rigid bodies, with internal degrees of freedom characterised by the rotation group SO(3), rather than rods, for which the internal configuration space is the two-sphere. Interest in biaxials has been stimulated in recent years with the synthesis and experimental study of new biaxial materials.

Previous theoretical investigations of phase transitions in biaxial liquid crystals have been mainly of mean field theory type, in which some additional phase symmetry is assumed a priori, and interaction energies are constrained to a simplified form.

The Onsager model is a prototypical density functional theory. It provides an analytical framework for computing phase diagrams of complex materials, and provides a means of proving (or disproving) some of the assumptions of mean field theory.

The project involves a rigorous analsysis of critical points of the Onsager free energy for biaxial nematics interacting via the Straley potential, a general interaction potential which includes many previously studied models as special cases. Methods include calculus of variations and bifurcations with symmetry.

Exotic states for quantum graphs (with JP Keating)

Quantum statistics refers to the behaviour of wavefunctions of identical particles under exchange of particles. For particles in three-dimensional Euclidean space, the spin-statistics relation says that many-body wavefunctions are either symmetric or antisymmetric (bosons or fermions) according to whether the particle's spin is integral or half-odd-integral. This relation has profound physical consequences (eg, the Pauli Exclusion principle, Bose-Einstein condensation). In two dimensions there are additional possibilities, even for spinless particles – anyon or fractional statistics, wherein wavefunctions change by a phase factor (not limited to 1 or -1) under exchange. Applications include the theory of the fractional quantum Hall effect.

One way to classify quantum statistics is to calculate the fundamental group of the n-particle configuration space - in which permuted configurations are regarded as the same, and particles are not allowed to coincide - and to determine its 1-dimensional representations (abelian statistics) as well as its higher-dimensional representations (nonabelian statistics, or parastatistics). In $\mathbb{R}^3$, for example, the fundamental group of n-particle configuration space is S_n, the symmetric group, whose 1-dimensional representations yield either Bose or Fermi statistics; in $\mathbb{R}^2$, the fundamental group is the (much larger) braid group B_n.

Quantum graphs - particles confined to a 1-dimensional network - have been much studied in recent years. They provide tractable models of interesting physical and mathematical problems, including quantum chaos (systems whose classical dynamics is chaotic), localization and phase transitions. The project is to investigate quantum statistics for particles on quantum graphs. The n-particle configuration space has a rich topology, and new forms of statistics appear. The project will also explore consequences of these exotic statistics, for example in recent models for topological quantum computers (which are based upon anyon and nonabelian statistics) as well as analogues of the fractional quantum Hall effect.

Quantization and topology of integrable systems: periodic Toda chain, singularities, and higher Maslov classes

Background: Singularities of finite-dimensional integrable systems are where the gradients of the constants of the motion become linearly dependent, and the foliation into tori degenerates (they are higher-dimensional generalisations of fixed points in 1-freedom systems). There is a body of work on the global topology of finite-dimensional integrable systems in which these singularities play a central role. There is also renewed interest in the semiclassical quantization of more-than-one-dimensional integrable systems, including quantization to higher orders in $\hbar$ and topological signatures such as monodromy. The periodic Toda chain is a well-known, non-separable, finite-dimensional integrable system. Gutzwiller initiated the study of the quantum problem in the early 1980s, and there have been important recent development, in particular concerning the quantum-integrability of the Toda chain (existence of observables commuting with the quantized Hamiltonian).

Recently I've been interested in a) the general relationship between integrable (codimension-one) singularities and the Maslov index which appears in the semiclassical (EBK) quantization conditions, and b) specifically the singularities of the periodic Toda chain, which turn out to be related in a nice way to eigenvalue degeneracies of the Lax matrix.

Research problems: a) Higher-order semiclassical quantization of the Toda chain. Recent work of Littlejohn et al and Colin de Verdiere gives a general geometrical framework for calculating higher-order $\hbar$ terms in the EBK quantisation scheme, but specific multidimensional systems have yet to be explored. The n-particle Toda chain is a good candidate for explicit calculations and for investigating the asymptotic behaviour of the semiclassical series for the energy levels. b) Investigate higher-dimensional Maslov classes (the next after the "Maslov index" requires at least 3 degrees of freedom), which should be related to higher-codimension singularities. Calculate higher Maslov classes for candidate integrable systems, and investigate their role on semiclassical quantisation.

Configurations of points in $\mathbb{R}^3$

Atiyah has constructed a certain natural map from C_n, the configuration space of n distinct and distinguishable particles in three-dimensional Euclidean space, to the flag manifold $U(n)/T(n)$ (here $U(n)$ is the unitary group, and $T(n)$ its maximal torus), which is equivariant with respect to permutations. Atiyah has conjectured that the map is continuous. The conjecture has been proved for $n = 1$ (trivially), 2 (easily), 3 (analytically) and 4 (by computer algebra), but for $n > 4$ remains open. One motivation for the problem arises from a nonrelativistic derivation of the spin-statistics relation for point particles in three dimensions.

A sharper formulation may be given in terms of conjectured properties of a certain n-body potential energy function, V_n, which is very interesting in its own right. V_n is invariant under translations, rotations, and dilations, and is constructed purely from Euclidean geometry. For $n = 3$ it is related to a certain many-body quantum potential due to Calogero and Marchioro for which some exact eigenstates can be calculated. Recent studies of minimum-energy configuration reveal striking similarities to, amongst other problems, minimum-volume sphere-packings and low-energy configurations of skyrmions.

Topics for PhD research include i) classical and (possibly) quantum dynamics of V_n, and ii) an algebraic study of its properties. Another direction iii) involves a generalisation due to Atiyah and Bielawski in which $U(n)$ is replaced by another classical Lie group $G(n)$, and C_n is replaced by the tensor product of $\mathbb{R}^3$ with the associated Lie algebra. One would like to generalise the related quantum theory, and find analogues of the spin-statistics connection, in this generalised Lie group setting.

4.13 Roman Schubert

My research covers several areas related to quantum mechanics, wave propagation and the theory of chemical reactions. In all these fields so called semiclassical approximations, which describe wave-propagation in the limit of short wavelength or high frequencies, are very important and these are my main field of research. The beauty of these methods lie in their combination of geometrical, dynamical and analytical arguments, one needs tools from the analysis of PDE's, symplectic geometry and dynamical systems.

My current two main research topics are the development of semiclassical approximations which remain accurate for large times, these are the basis for rigorous proofs of wave chaos, and the development of quantum transition state theory, which describes chemical reactions, for large molecules.

Projects in these areas can range from developing new rigorous mathematical techniques to applications in concrete systems involving numerical simulations. Students interested are welcome to contact me for references and to further discuss suitable projects.

4.14 Martin Sieber

My research is in the field of quantum chaos which, strictly speaking, is the study of quantum systems whose underlying classical system is chaotic. However, the scope of this field has widened considerably in recent years. It comprises now the study of many different wave phenomena in fields like quantum mechanics, electrodynamics and acoustics. Generally speaking, one tries to understand how the distribution of waves depends on the shape of objects (cavities, quantum dots, resonators) in which they are contained.

An important analytical method is the asymptotic approximation in the limit of short wavelengths, for example the semiclassical approximation in quantum mechanics or the geometrical optics approximation. As well as giving often a surprisingly accurate description these short-wave approximations also allow us to understand wave phenomena in terms of objects that we are more familiar with: trajectories in semiclassical approximations or rays in geometrical optics. Some of my projects are the following:

Short-wave approximations in dielectric cavities: Micron-size dielectric cavities are often used in microoptics applications. Short-wave approximations for these systems are, however, much less established than for corresponding quantum systems. For example, the range of validity of a two dimensional approximation that is often used for thin dielectric disks is not known. Furthermore, a systematic derivation of certain asymptotic formulas in the short-wave regime is lacking. The project involves the development of asymptotic methods for these systems.

Quantum mechanics of open chaotic cavities: One of the most significant discoveries in the field of quantum chaos has been the connection to Random Matrix Theory (RMT). One finds, for example, that statistical distributions of energy levels in chaotic systems agree with those of eigenvalues of random matrices. The agreement with RMT extends to many other quantum statistics. However, if one opens the system up, for example by attaching leads to a cavity, one starts to see deviations from RMT. Semiclassically this can be explained in terms of trajectories that leave the system in a short time. The project involves the investigation of open chaotic cavities and their connection to RMT.

Semiclassical wavefunctions in chaotic systems: This is a project with a large numerical component. A recently developed semiclassical theory expresses wavefunctions in chaotic systems in terms of trajectories of the corresponding classical system. The properties of this approximation have not yet been investigated numerically. It is expected that a systematic investigation would require quite extensive numerical calculations.

Semiclassical approach to spectral statistics: The connection between quantum chaos and Random Matrix Theory that was mentioned above has not been proved rigorously. However, there exists a semiclassical approach that provides an explanation for this connection. According to this approach it is due to correlations between periodic orbits in the classical system. It is one of the most important open problems how to put this semiclassical approach on a firmer basis. The project pursues this aim by investigating terms in the semiclassical theory that have been neglected so far.

There are close connections to research interests of Prof. J. Keating and Dr S. Müller.

4.15 Valeriy Slastikov

Please contact Dr Slastikov directly. A jointly supervised project on the Onsager model for phase transitions in biaxial liquid crystals is described in Jonathan Robbins' entry, and another jointly supervised project is described in Isaac Chenchiah's entry.

4.16 Nina Snaith

My research interests are in quantum chaos and random matrix theory, but in particular in the application of random matrix theory to number theory. Random matrix theory was developed in the context of nuclear physics to predict the statistics of the eigenenergies of complicated nuclear systems. However, in the 1970s, it was shown that the Riemann zeta function (a function much studied by number theorists and subject of the famous Riemann Hypothesis) has zeros that show the same statistics as these nuclear energy levels. So, random matrix theory has become a powerful tool to study number theoretical functions like the Riemann zeta function and other L-functions.

Current projects in this area involve applying random matrix theory to mean values of the Riemann zeta function and other L-functions, to the order of zeros of L-functions at the critical point (in connection with the conjecture of Birch and Swinnerton-Dyer) and in the distribution of prime numbers.

Projects in this area can involve both numerical and analytical work and students will learn techniques that are of use both in mathematics and physics.

4.17 Yves Tourigny

My recent research has been on the following themes: (1) The study of the spectral properties of Schrödinger operators with a random potential. (2) The connection between diffusion processes and the Schrödinger equation with "supersymmetric" potentials. (3) The study of products of random matrices. For a detailed description of the results obtained recently, and of the techniques used, see

`http://arxiv.org/find/all/1/all:+tourigny/0/1/0/all/0/1`

Roughly speaking, work on these problems involve an exciting blend of probability, differential equations, and mathematical physics. I am happy to discuss with prospective students projects that extend this work or are closely connected to it.

4.18 Karoline Wiesner

I like to summarize my research as follows. Nature stores and processes information - it intrinsically computes. Scientists have successfully described various physical processes as a computation - among others: Crystal growth, molecular self-assembly, DNA transcription. Some of these are quantum, others are classical computations. Can we find the correct computation-theoretic description in general? What can we learn from it about the intrinsic computational capacity of these processes? I develop (quantum) computation-theoretic representations of physical systems, using tools from information theory, hidden Markov models, quantum Markov processes, probabilistic and quantum finite-state machines.

If you are interested in studying the information-theoretic properties of these representations, their application to physical systems, or other related topics, please, come and talk to me.

For more information, see (http://www.maths.bris.ac.uk/~enxkw).

4.19 Andreas Winter

The following PhD projects are exemplary but not exhaustive for what I could supervise. I am an information theorist with a background in probability theory and quantum mechanics and an interest in combinatorics; these are the approximate boundaries of my expertise.

Information theory

Maurer and Ahlswede/Csiszar have shown how to treat cryptographic key distillation in an information theoretically optimal way, from statistical assumptions, in some restricted models. Many questions remain: for example, what is the ultimate key yield? Or, following Wolf and Gisin: is there "bound information" in the sense of genuine correlation which nevertheless does not allow extraction of secret key? In recent work with Japanese colleagues I found rates for other cryptographic tasks, bit commitment and coin tossing, again from statistical assumptions. These are optimal in the case of bit commitment. For coin tossing this is still open, and for the important primitive of oblivious transfer there does not even exist a lower bound.

Quantum information theory

In a joint work with Devetak, I characterized the amount of secret key obtainable from a quantum state, in a restricted model. Like in the classical model, the ultimate key rate is still open. Also, there is a connection to entanglement distillation, which allows in principle to characterize the optimal distillation rates but the formulas are "non-computable" as they involve infinite dimensional optimizations. A better understanding, or at least easily computed bounds would be extremely interesting. Noah Linden offers a project on quantum entanglement which focuses on multi-party systems. Also these pose optimal rate problems about which almost nothing is known, but which could be tractable by the recently developed methods. In general however, it is felt that new ideas are needed.

Coding theory

Even though I am not an expert, I would be able to supervise an able student. A question about "small" codes which I find particularly intriguing is the so-called Hadamard conjecture: it says that there exists an n-by-n orthogonal matrix with all entries +1 or -1 if and only if n=2 or n is divisible by 4. This boils down to constructing such 1 orthogonal matrices (Hadamard matrices) for all orders 4k. The problem is equivalent to constructing binary codes of length 4k on 4k bits with Hamming distance 2k.