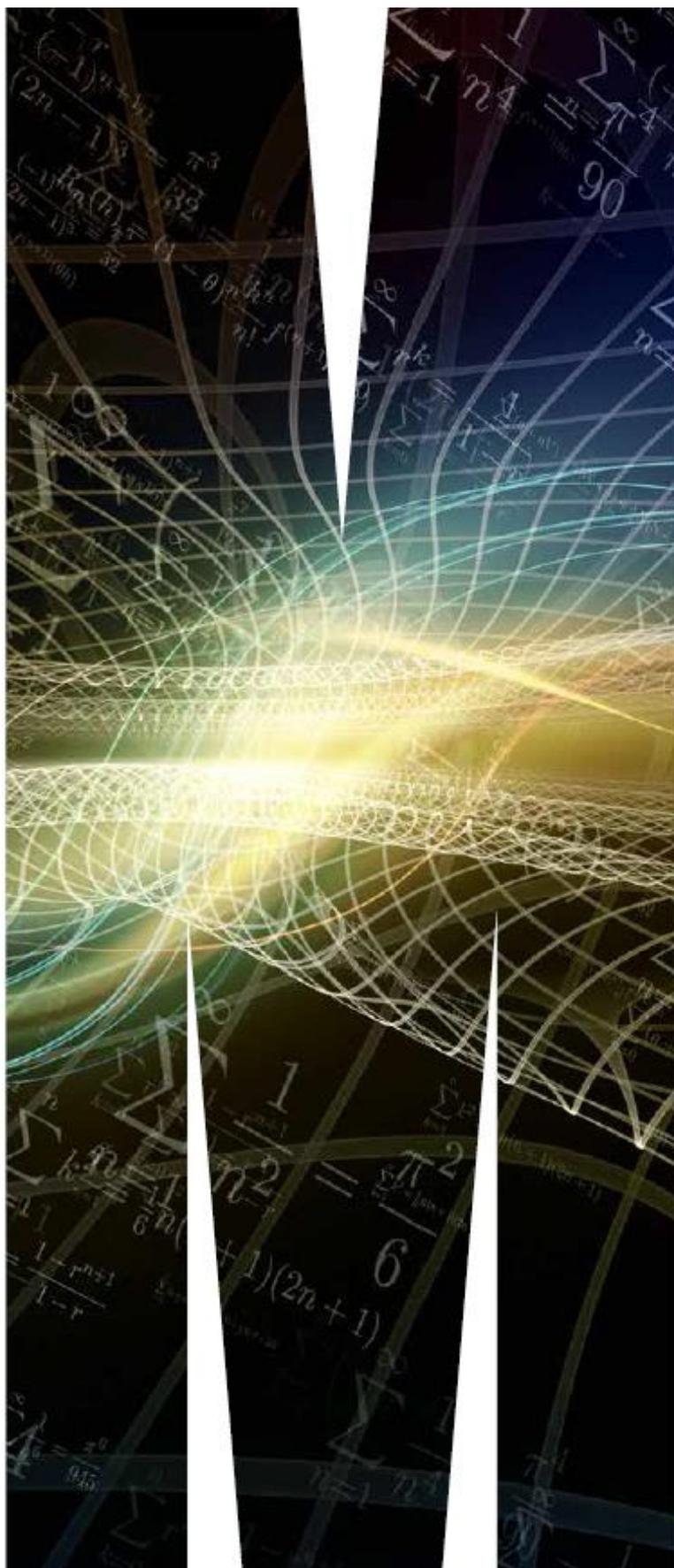




# School of Mathematical Sciences

Honours research  
projects  
2019

MONASH  
SCIENCE



Projects are listed by Supervisor.

(A) Applied mathematics, (P) Pure mathematics, (S) Stochastic Processes & Statistics, (F) Financial Mathematics

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# INTRODUCTION - Honours research projects

The honours year is split in two: a “research project unit” component (MTH4100) and a coursework component (MTH4200).

## **MTH4100 – Mathematics research studies (24 points)**

M40110 - Writing and Presenting for Honours (3 points)
<b>Research project (15 points)</b>
One fourth year honours lecture unit (6 points)

### **Assessment for Research projects**

1. Intermediate report. (25% of project mark ) Due 4pm last Friday first semester.  
Comprising of a literature survey, and discussion of any new mathematical techniques that you needed to complete the project.  
Recommended length: 10-20 pages.  
Assessed by supervisor.
2. Final report: (60%) Due 4pm last Friday of second semester.  
Recommended length: 25-40 pages.  
Assessed by supervisor and two other staff members.
3. Oral presentation: (15%). During swotvac, second semester. Assessed by all staff who attend the Honours presentations.

### **More information**

The time you spend on the intermediate report and the project should be similar to the time spent on the equivalent (credit points-wise) number of lecture topics. You should start your intermediate report and project at the beginning of your first semester. It is also advisable to meet your supervisor regularly, say once a week, as soon as the teaching semester begins

Late submissions for Assignments and Reports will be penalised with 10% per day or part thereof late, including weekends. Work submitted more than 1 week late without special consideration will not be marked. This is in accordance with the Faculty of Science policy: <http://intranet.monash.edu.au/science/staff/education/policies-procedures/late-submission.html>.

You should also keep a COPY of any submission for your records.

This booklet is intended to provide an overview of the research activities within the School of Mathematical Sciences and to give you an indication of the Honours projects that will be offered in 2017.

You are encouraged to study these and to speak with the research supervisors. This research project plus the required course work component on writing and presenting make up 75% of the final mark for the unit MTH4100, with the other 25% from a first semester coursework component.

Current third year students are eligible to do Mathematics Honours (Clayton) in 2017 provided they fulfil the entry requirements and that a supervisor is available.

Students will be allocated to supervisors and projects on the basis of their third year results and their preferred projects. Great care is taken to ensure that all students are treated equitably and where possible that they are be allocated to the area and supervisor of their choice.

All Honours candidates must discuss prospective projects with at least four supervisors before choosing their preferred project. They should then select at least three potential supervisors and projects in order of preference. The application forms – one for Honours entry which is from the Faculty of Science, the other is the project nomination form which is from the School of Chemistry – are both available on the School of Chemistry web page.

Please note that the project descriptions are quite short, and more comprehensive details can be obtained when speaking to supervisors.

We look forward to seeing you in the Honours course next year. Please contact me if you have any questions about the Honours year!

## **The travelling salesman problem and understanding what makes it hard (A)**

Background: The Travelling Salesman problem (TSP) aims to find the shortest path that connects a set of cities and returns to the starting city. It is an example of a combinatorial optimisation problem, with many practical applications such as logistics and transportation planning, telecommunications routing, and is known to be NP-hard. What we don't know is how the location of the cities and their statistical properties affects the relative hardness of a particular instance of the TSP for different algorithms or methods.

Project outline: This project commence with a study of the statistical properties of TSP instances that are known to affect the hardness of the problem. Much work has been done of identifying parameters that control the easy-hard transition. You will then generate hundreds of TSP instances, solve them using a variety of methods, and then examine the correlation between the characteristics of the instances and the performance of algorithms. Our goal is to be able to explain why some algorithms perform well for some TSP layouts (distribution of cities) and poorly for others. Please note: Many other projects are available with Kate Smith-Miles which take a similar approach to different optimisation problems, such as graph colouring, knapsack, bin-packing, timetabling, etc.

References:

- [1] Smith-Miles, K.: "Cross-disciplinary perspectives on meta-learning for algorithm selection" ACM Computing Surveys 41(1) (2008)
- [2] Gent, I., Walsh, T.: "The TSP phase transition" Artificial Intelligence 88(1-2), 349\_358 (1996)
- [3] Johnson, D.: "Experimental analysis of heuristics for the ATSP" Chapter 10 in: The Travelling Salesman Problem and Its Variations. G. Gutin, AP Punnen (2002)

## **The travelling salesman problem with dynamic time windows (A)**

Project Outline: In this project we consider the new version of Travelling Salesman Problem (TSP), the so-called travelling salesman problem with dynamic time windows (TSPDTW). In TSPDTW the cities have partial precedence relations and the salesman must visit a city within a given time window since visiting the previous city. The goal is to find the route that requires the shortest time to visit each city exactly once. It can be shown easily that the TSPDTW is NP-hard. This problem arises in robot scheduling problems where jobs needs to have certain buffer time between operations.

In this project the student will develop exact and heuristic algorithms for the TSPDTW.

Pre-Requisites: Basic knowledge in programming, knowledge of Linear Programming, scheduling, heuristic algorithms is helpful but not essential

## **Job shop scheduling with min/max separation (A)**

Project Outline: In this project we consider the job shop scheduling problem with min/max separation constraints. The challenge of scheduling jobs with min/max separation constraints is found in many real world problems. However, little of the existing literature has focused on methods to deal with min/max separation constraints. It is an extension of classical job shop scheduling problem. Job shops with either positive or negative time lags have been considered in the literature. However, only a few papers have considered job shops with both positive and negative time lags (min/max separations). The algorithms developed with either positive or negative time lags do not produce feasible solution for job shops with min/max separation constraints.

In this project we will focus on minimisation of makespan. The student needs to develop heuristic algorithms and techniques to find a feasible solution of the problem.

Pre-Requisites: Basic knowledge in programming, knowledge of Linear Programming, scheduling, heuristic algorithms is helpful but not essential

References:

- [1] P. Lacomme, N. Tchernev , M.J. Huguet . Dedicated constraint propagation for Job-Shop problem with generic time-lags , IEEE ETFA , pp 1-7, 2011
- [2] A. Caumonda , P. Lacommea, N. Tchernev. A memetic algorithm for the job-shop with time-lags Computers & Operations Research, 35, pp 2331 – 2356 , 2008

[3] A. Oddi, R. Rasconi, A. Cesta, S. Mith. Solving job shop scheduling with setup times through constraint-based iterative sampling: an experimental analysis. *Annals of Mathematics and Artificial Intelligence*, 62, Issue 3-4, pp 371-402, 2011.

## The analysis of Willmore surfaces (P)

Erythrocytes (also called red blood cells) are the body's principal mean of transporting vital oxygen to the organs and tissues. The "inside" of an erythrocyte is rich in haemoglobin, which chemically tends to bind to oxygen molecules and retain them. To maximize the possible intake of oxygen by each cell, erythrocytes – unlike all the other types of cells of the human body – have no nuclei. The membrane of a red blood cell is such that it isolates the "inside" from the "outside". One might be tempted to conclude that in order to maximize volume as "densely" as possible, red blood cells should be spherical. This is however not at all true (having spherical red blood cells is a serious disease). In fact, when incorporating into the problem that the membrane of a red blood cell is an elastic surface, one is led to the so-called the Willmore energy. It appears in various areas of science: cell biology, but also in elasticity theory, in optics, and even in general relativity. I am offering three reading projects on the analytical aspects of the Willmore energy with different focus points. Each project will consist in reading and understanding two articles from the recent literature, as well as to reformulate certain crucial proofs. At the end of the reading project, the student will be familiar with Willmore surfaces and with the various analytical techniques involved in the study of the 4th order nonlinear Willmore equation.

References:

[1] Y. Bernard, G. Wheeler, V. Mira-Wheeler "Local analysis of the inhomogeneous Willmore equation", preprint to appear.

[2] Y. Bernard, T. Rivière "Singularity removability at branch points for Willmore surfaces", *Pacific J. Math.* 265 (2013), no. 2, 257-311.

**Research Project No. 1: Variational considerations.** The student will learn how to apply Noether's theorem to the Willmore functional as well as to other important functionals appearing in geometric analysis in order to derive conservation laws. These laws will be used to understand various analytical and geometric properties of Willmore surfaces.

**Research No. 2: Local analytical aspects.** The student will learn in details how to study the regularity of the solutions to the Willmore equation, as well as to inspect the asymptotic behaviour of a branched solution (i.e. one with point singularities).

**Research Project No. 3: The compactness question.** In this reading project, the point of focus will be to understand how one can extract from a given sequence of solutions to the Willmore equation a subsequence that converges in an appropriate sense, and to understand the analytical and geometric properties of the limit.

## Variational methods in shape optimisation (A,P)

(co-supervised with Dr Janosch Rieger)

Shape optimisation has various applications in theory as well as in industry. The minimisation of the drag of a vehicle, the maximisation of the effectiveness of a magnet with given weight in a wind turbine and the reconstruction of the most likely shape of an object by tomography are particular examples of shape optimisation problems.

From a mathematical perspective, a shape optimisation problem is an optimisation problem, where the optimisation variable is a subset of a Euclidean vector space. As the collection of these subsets has no linear structure, standard approaches to optimisation problems do not work in this setting.

The aim of this project is to work through the first chapters of the books *Introduction to Shape Optimisation* by Sokolowski and Zolesio and *Variational Methods in Shape Optimisation Problems* by Bucur and Buttazzo to obtain a thorough understanding of the problem as such. The second step will be a numerical treatment of a selected shape optimisation problem.

The prerequisites for this project are a solid knowledge in real analysis and linear algebra. Familiarity with functional analysis, partial differential equations, nonlinear optimisation and computational mathematics is beneficial, but not required.

## Solving the Rubik's cube and the Rush Hour puzzle (A)

Background: We all know how frustrating the Rubik's cube can be and it is tempting to either hit it with a hammer or use a published algorithm to solve the cube (though it is much more rewarding to find your own solution). Another fun puzzle is the so called Rush Hour puzzle where you slide blocks (that represent cars), horizontally and vertically, over a grid (the grid lock of cars) to free your car from the grid lock.

Project Outline: Problems of this sort can be solved by brute force where every possible move is tried and eventually a solution is found. This is a dumb way to proceed and is not something you should feel proud about (not to mention that such strategies may take far too long to be practical). A better approach uses statistical sampling to efficiently search through the set of all possible moves to find a solution. In this project we will look at two popular methods, genetic algorithms and simulated annealing. Both methods draw upon paradigms from other areas of science where the dynamics of certain physical processes (e.g. evolution and the formation of crystals) can be described as an exercise in optimization (e.g. survival of the fittest, minimum energy principles).

We will use both genetic algorithms and simulated annealing to solve both the Rubik's cube and the Rush Hour puzzles. The project will involve a mix of computer programming (in any language you prefer) and standard mathematical tools. The creative element in this project will be how you apply the methods to these problems.

## Constructing initial data for Brill waves (A)

Background: Einstein's theory of gravity is described by ten coupled non-linear partial differential equations for ten metric components  $g_{\mu\nu}$ . These equations can be solved by either analytical or numerical methods but not without some difficulty -- the equations are very messy!

Project Outline: In this project we will construct time symmetric initial data for a spacetime with axial symmetry (i.e. a spacetime that is symmetric under rotations around the z-axis). This initial data will represent the geometry of a universe whose curvature is generated by a Brill wave (a pure gravitational wave). This task of constructing such initial data is a non-trivial problem as it requires the solution of a single second order non-linear elliptic pde in two dimensions. The formulation of this pde is unconventional in that we will employ a novel lattice method to record the geometry of the space. The pde will be expressed in local Riemann normal coordinates (closely related to the freely falling frames often used in General Relativity).

The numerical methods required to solve the pde will be non-trivial and will range from simple iterative schemes through to non-linear multigrid methods. Unfortunately we do not have any analytic solutions to compare our answers to but there are many numerical results.

This project will introduce you to active research in numerical relativity. You will need to be comfortable with sophisticated numerical methods as well as classical general relativity and differential geometry. This project is intended for those who would like to continue studies in numerical relativity at the postgraduate level.

References:

- [1] Eppley, Kenneth, "Evolution of time-symmetric gravitational waves: Initial data and apparent horizons". Phys.Rev.D. Vol.16 (1977) pp.1609-1614
- [2] Brewin, Leo, "Riemann Normal Coordinates, Smooth Lattices and Numerical Relativity. Classical and Quantum Gravity". Vol.15 (1998) pp.3085-3120
- [3] Brewin, Leo, "Long term stable integration of a maximally sliced Schwarzschild black hole using a smooth lattice method". Classical and Quantum Gravity. Vol.19(2002) pp.429-456.

## Maximal slicing of a Schwarzschild black hole (A)

Background: The Schwarzschild black hole is the simplest solution (beyond flat space) of the vacuum Einstein field equations. It can be used to describe the gravitational field outside a static, non-rotating spherical object. A common way to study this (and many other spacetimes) is to follow the evolution of a 3-dimensional spacelike hypersurface in a 4-dimensional spacetime. This is the so-called 3+1 split of space and time.

This can be viewed either as a single 3-dimensional hypersurface on which the 3-metric evolves with time or as a sequence of separate 3-dimensional hypersurfaces stacked on top of each other (without intersections) so as to fill a portion of (or if we are lucky all of) the 4-dimensional space time. In this later approach, the collection of slices is known as a foliation of space time.

Project Outline: Beig and Ó Murchadha have studied a particular foliation known as maximal slicing in which the local volume element (of a small 3-dimensional cell) remains constant when propagated along the normals to each slice of the foliation (i.e. the trace of the second fundamental form is zero for all time). They showed that such slices converge to a limit slice (i.e. maximal slices do not foliate the whole of the spacetime) and they also presented integral expressions by which these slices can be constructed. However the integrals require great care when being evaluated numerically (they are improper elliptic integrals). The point of this project is to study the paper by Beig and Ó Murchadha and to write a computer program that can accurately evaluate the integrals for slices close to the limit slice.

This project will introduce you to active research in numerical relativity. You will need to be comfortable with sophisticated numerical methods as well as classical general relativity and differential geometry. This project is intended for those who would like to continue studies in numerical relativity at the post-graduate level.

#### References

[1] Beig, R and Murchadha, N, "Late time behaviour of the maximal slicing of the Schwarzschild black hole" Phys.Rev.D. Vol.57 (1998) pp.4728 – 4737.

## The spectrum of quantum graphs (P)

Consider the tones produced by a struck drum. The fundamental tone is the lowest, dominant note, but there are also overtones, a sequence of higher notes sounded simultaneously. In the simplest model, these tones depend entirely on the geometry of the drum surface.

These tones can be expressed mathematically as the eigenvalues of the Laplace operator: a sequence of numbers  $\lambda_1 < \lambda_2 \leq \lambda_3 \leq \dots$  (collectively called the spectrum), with corresponding eigenfunctions  $\phi_1, \phi_2, \dots$  satisfying  $\Delta\phi_i + \lambda_i \phi_i = 0$  (and appropriate boundary conditions). They depend on the geometry of the domain.

For this reason, the question of determining the geometry of a domain from the eigenvalues is often described as “can one hear the shape of the drum?” (after Kac).

This problem has two natural analogues for graphs. The first is discrete: the Laplacian operator is discretised, and the spectrum relates to graph invariants, such as connectivity, isoperimetric number, maximum cut, independence number, genus, diameter, and bandwidth-type parameters of a graph.

However here we will concentrate on a second graph setting which has recently attracted some attention: the so-called metric or quantum graphs. Here the one-dimensional Laplacian is defined along each edge, with compatibility conditions imposed at vertices. These are so-called quantum or metric graphs, and in this setting the length of edges is now important. We will investigate the spectral properties of such graphs and look at connections between optimal bounds and geometric invariants.

Prerequisites: solid background in analysis and PDE (MTH3011 Partial differential equations, MTH3140 – Real analysis). You should also take the Honours PDE subject M41022, the Functional Analysis course MTH3160 is recommended, and you may find the Honours Graph Theory course M41072 useful (although by the time second semester comes around you may have already covered the relevant territory).

References:

[1] Berkolaiko and Kuchment, Introduction to quantum graphs, AMS2013.

[2] Kac, Can one hear the shape of a drum? Amer. Math. Monthly, 1966

[3] Jarret, Michael and Jordan, Stephen P., The fundamental gap for a class of Schrödinger operators on path and hypercube graphs, 2014.

## Hyperbolic curvature flows (P)

(co-supervised with Dr Pascal Buenzli – QUT)

This project aims to study the evolution of plane curves under the action of a curvature-dependent normal acceleration. These flows are motivated by the evolution of biological surfaces (such as the bone interface) when new layers of material are deposited by cells lining the material’s surface. Numerical evidence suggests that when cell diffusion is very low or very high, such flows lead to the emergence of shocks (corners in the interface) after which weak solutions must be sought. However, at intermediate diffusivities, the interface remains smooth at all times. These behaviours will be investigated rigorously using hyperbolic curvature flows.

## The mountain pass technique in modern geometry (A)

In many natural physical and mathematical situations, we want to not only minimise an energy, but also find its critical points-- places where may be only local maxima or minima, or even saddle points. One strategy to address this delicate problem is the mountain pass technique, where we look for points that have minimise energy in one direction, but maximise it in others--- like finding the lowest point of a mountain range in order to cross it.

This project will study the evolution of the technique, from the classic variational techniques it developed from, to its use in geometric problems such as finding closed geodesics on manifolds, and recent developments such as Coda Marques and Neves' proof of the Willmore conjecture.

**Prerequisites:** solid background in analysis and PDE (MTH3011 Partial differential equations, MTH3140 – Real analysis). Metric spaces MTH3160 and Differential Geometry 3110 would be useful.

**Topic on random walks (S)**

Description to come

**Topics on large deviations (S)**

Description to come

## **Magneto-rotational instability in very high speed flows (A)**

**Background:** The origin of turbulence observed in proto-planetary accretion around celestial bodies remains unclear despite decades of research. Purely hydrodynamic theory predicts that Keplerian motion, which any orbital matter under central gravitational force obeys, is stable. Hence certain entanglement of magnetic and velocity fields has been thought as a promising framework to explain the observed instability. The difficulty encountered by previous studies of proto-planetary accretion disk in adopting a magneto-hydrodynamical approach lies in the fact that unless the flow speed is very large, which is unreachable in existing simulations and experiments, the stability is almost unchanged from the purely hydrodynamic cases.

**Objectives:** In this project we aim to study the fate of the stability by taking the high speed limit of the governing equations restricting our attention to a simple flow configuration between an annulus. The reduced equations found at the asymptotic limit will be solved numerically or analytically. The asymptotic solution will then be compared with the full numerical solution.

**Assumed knowledge:** Basic knowledge of fluid mechanics, differential equations (e.g. MTH3011, MTH 3360) and programming language (e.g. FORTRAN or MATLAB) are desirable.

### **References:**

- [1] Velikhov, E. P. 1959, Soviet. Phys. JETP 36, 1389-1404.
- [2] Chandrasekhar, S. 1960, Proc. Nat. Acad. Sci. 46, 253-257.
- [3] Balbus, S. A. & Hawley, J. F. 1991, Astrophys. J. 376, 214-222.
- [4] Grossman, S., Lohse, D. & Sun, C. 2016, Annu. Rev. Fluid Mech. 48, 53-80.
- [5] Rudiger, G. et al. 2018, Phys. Rep. 741, 1-89.
- [6] Deguchi, K. 2016, J. Fluid Mech. 808, R2.

## Topics in (computational) algebra (P)

If you have completed Algebra and Number Theory I (& II), and if you are interested in the area of algebra, then you can discuss possible projects with Heiko, [heiko.dietrich@monash.edu](mailto:heiko.dietrich@monash.edu)

Depending on background and interests, topics can be chosen from the broad areas of:

- Group Theory,
- Lie algebras,
- Coding Theory / Cryptography,

or from any other suitable area in algebra; feel free to discuss your preferences.

If interested, then a project could be tailored to involve the computer algebra systems GAP ([gap-system.org](http://gap-system.org)) or MAGMA ([magma.maths.usyd.edu.au/magma](http://magma.maths.usyd.edu.au/magma)).

Skills required: Interest in algebra and understanding of pure maths proofs.

Prerequisites: Algebra and Number Theory I (& II).

## Tropical enumerative geometry (P)

**Background:** How many lines pass through two randomly chosen points? OK, so that's an easy one. But how many degree two curves in the plane pass through five randomly chosen points? And what happens when you consider higher degree curves? This problem from the realm of *enumerative geometry* was studied for centuries before being resolved by the Fields medallist Maxim Kontsevich in 1995 using ideas from theoretical physics. In the last several years, a new and relatively simple approach to such problems has arisen from the world of *tropical geometry*.

**Project outline:** There are many possible projects, depending on the preferences and strengths of the student. The initial goal would be to understand the basic notions of tropical enumerative geometry. From that point, a student could explore the notion of tropical Hurwitz numbers or the rich algebraic structures that arise in tropical enumerative geometry,

### References

- [1] G. Mikhalkin. What is... a tropical curve? (2007)
- [2] R. Cavalieri, P. Johnson and H. Markwig. Tropical Hurwitz numbers (2008)

## The algebra of knots (P)

**Background:** A knot is made by taking a piece of string, tying it up in some fashion, and then gluing the ends together. For well over a century, mathematicians and scientists have been preoccupied with the question of how to distinguish two given knots. Over recent decades, inspirations from algebra and theoretical physics have led to a vast theory of knot polynomials, which help to answer this question. A particularly important example is the sequence of coloured Jones polynomials.

**Project outline:** There are many possible projects, depending on the preferences and strengths of the student. One is to examine the AJ conjecture, which relates the recursive structure of coloured Jones polynomials with the A-polynomial of a knot. Another is to consider modern approaches to the volume conjecture, which relates coloured Jones polynomials with the volume of a space related to the knot. Physicists have recently proposed that these conjectures can be investigated using a theory known as topological recursion.

### References

- [1] C. C. Adams. The knot book. (2004)
- [2] H. Murakami. An introduction to the volume conjecture. (2010)

## Hedging with delay and portfolio constraints (F)

**Abstract:** This paper deals with super-replication of European options in financial markets with delay. Namely, we consider the following setup. At time  $t$  the investor gives an order to buy a number of shares, however the order is executed only at time  $t+h$ . Thus,  $h>0$  is the market delay.

Clearly, in a continuous-time model, if the risky asset has unbounded fluctuation on any finite (deterministic) time interval, then super-replication in a delayed market in general is impossible. This is the case, for instance in the Black-Scholes model.

The goal of the proposed project is to study the limiting behaviour of super-replication prices in the Cox-Ross-Rubinstein (CRR) binomial models. We fixed a natural number  $H$  and assume that the delay equals to  $H$  trading times. With this type of scaling, our conjecture that super-replication prices in the CRR models should converge to the  $G$ -expectation of Peng.

## **Solar quakes (A)**

(co-supervised with Prof Paul Cally)

Background: Helioseismic holography is a technique used to image the sources of seismic disturbances observed at the solar surface. It has been used to detect acoustic emission, known as sun quakes, radiated from X-class solar flares. Since the seismic power emitted by the X-class flares has proved to be independent of the strength of the flare, we have undertaken a systematic search for seismic signatures from C to X-class solar flares, observed by SDO satellite. We have detected significant acoustic emission from a few C and M-class solar flares

Aims: An exhaustive search for sunquakes, focusing on detections as close to the solar limb as possible.

Tools: unix scripts, unix friendly environment, easy to learn

Prerequisite: MTH2032 or equivalent, love for solar physics

References: ADS/NASA: search for the supervisor's name.

## **Local thermodynamic equilibrium in highly ionized plasma: solar physics application (A)**

Background: Atoms in a gas have a spread in thermal energy and they collide with each other. Sometimes there is a collision with high enough energy to knock an electron out of the atom and ionize it. Energy must exceed ionization potential, 13.6 eV for hydrogen. In a cold gas such collisions are very infrequent, in a hot gas more likely. Photoionization can be also important. Processes of deionization (recombination) will be also analysed under solar flares and supernovae conditions.

Aims: Calculation of the ionization state for LTE plasmas.

Tools: C codes, unix friendly environment, easy to learn.

Prerequisite: MTH2032 or equivalent, love for solar physics, basic understanding of physics (atomic).

References: ADS/NASA: search for LTE plasma, ionization, Saha-equation

## **A multi-wavelength view on coronal rains (A)**

Rain, rain, go way...come again some other day!

Magnetic coronal loops become unstable and mass flows of plasma is initiated during coronal mass ejections (CMEs). Cool plasma in hot and dense coronal loops, rapidly produced in the corona (timescale of minutes) falls down to the chromosphere along loop-like paths. They are observed only in active region loops and the falling speeds are lower than free fall speeds.

With the advent of the AIA instrument on the famous Solar Dynamic Observatory, we intend to look into the physical properties of coronal rains. We will outline loop structures, extract data along loops, generate space-time diagrams, and deduce projected velocities.

References

[1] Antolin P (2012) arXiv:1203.2077

## **The magnetic fields of the quiet sun (A)**

Who said that the Quiet Sun is boring? Our understanding of the quiet Sun magnetic fields has turned up-side-down during the last decade. The quiet Sun was thought to be basically non-magnetic, whereas according to the current views, it is fully magnetized.

In this project we will summarize the main observational properties of the quiet sun magnetic fields. Magnetograms from the Helioseismic and Magnetic Imager (HMI) instrument on board of the Solar Dynamical Observatory will be analysed.

We then address specific properties of the quiet Sun magnetic fields: the distribution of magnetic field strengths and unsigned magnetic flux, the distribution of magnetic field inclinations, and the time evolution of the signals on short time-scales.

References

[1] J. S´anchez Almeida and M. Mart´inez Gonz´alez, arXiv:1105.0387v1 [astro-ph.SR] 2 May 2011.

## **The photospheric velocity field of active regions derived from SDO/HMI data (A)**

Amazing project on active regions of the Sun, probably the most interesting features on the solar surface. Solar active regions are observed with the Helioseismic and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO). Since HMI continuously observes the complete solar disk at a good spatial resolution we are able to follow active regions over several days, providing the opportunity to study the evolution of the flow field during the various stages of development of the active regions. HMI measures the photospheric vector magnetic field at a cadence of 12 min. The intensity continuum maps are taken at a cadence of 45 seconds.

To determine the velocity field we use the optical flow technique DAVE4VM (differential affine velocity estimator for vector magnetograms) and apply it to the vector magnetic field data from SDO/HMI. We will learn about this technique and its use. This project gives the student the general view of the state-of-art solar data from the satellite and how to interpret the observations. The project is new, the student and the lecturer will work step by step, together, to discover the use of the DAVE4VM code.

References:

[1] [http://ccmc.gsfc.nasa.gov/lwsrepository/DAVE4VM\\_description.php](http://ccmc.gsfc.nasa.gov/lwsrepository/DAVE4VM_description.php)

[2] <http://wwwpppd.nrl.navy.mil/whatsnew/dave/index.html>

## **In search for the solar quakes of cycle 24 (A)**

This is a purely observational project, with exciting steps every time you will detect a REAL sunquake. We will create a database of sunquakes generated by solar flares during the cycle 24.

The project involves handling large amounts of data cubes, and the existing helioseismic holography software (C language, Unix scripts, IDL). The data used for this work are from the Helioseismic and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO).

This project will help in detection of new sunquakes, with the main aim of having an immediate publication of the results with the discoverer as the main author.

## **Simulations of seismic triggers on the solar photosphere (A)**

Do you want to trigger your own solar quake into the solar photosphere?

Acoustic disturbances observed at the solar surface are applied to the surface of a model of the quiet Sun and propagated backwards in time into the model interior. A particular point in the model at which the regressed acoustic field is sampled is called a focus, or focal point of the computation. In practice the egression at a given focus is computed for surface disturbances over a limited region overlying the focus, called the pupil of the computation. A surface over which the regressed acoustic field is sampled is called a "focal surface," or "focal plane" if the plane-parallel approximation applies. A adaptation called "subjacent vantage holography" ( of Lindsey & Braun 2000) has been used to image surface sources, as flares (Donea, Braun & Lindsey 1999; Donea & Lindsey 2005; Donea et al. 2005; Donea et al. 2006, Moradi et al. 2007) and acoustic emission halos surrounding active regions (which Donea, Lindsey & Braun 2000, called "acoustic glories"). Donea, Lindsey & Braun (2000) applied subjacent vantage holography to the quiet Sun over the 57 mHz spectrum and did statistics on the surface acoustic power maps these computations yielded. We apply the same technique to simulations of acoustic disturbances from dipole sources. In these studies the focal plane is at the surface, and the pupil is an annulus of radial range 1560 Mm centred on the focus.

This may seem a complicated topic, but it is beautiful because the simulations generated by the existing codes, will make the student to enjoy running various source motion on the photosphere, in a Unix environment. We start with looking at an acoustic field generated by a single source, then we add complex structures and movement to the source.

## **TeV gamma ray absorption from binary black holes (A)**

Binary black holes are fascinating systems. If you do not fear a bit of physics and some theoretical astrophysics concepts, then this project is for you. We will do everything together, from computer coding till literature reading.

We show that the gamma-gamma opacity of GeV and TeV photons emitted by relativistic jet, travelling in the external photon environment of a binary supermassive black hole system, cannot be neglected when studying the emission of active galaxies. A primary supermassive black hole surrounded by a standard accretion disk in symbiosis with a relativistic jet is assumed to revolve in a co-planar orbit together with a secondary black hole surrounded by a viscous Shakura-Sunyaev small accretion disk. We investigate to what extent the location of a gamma-ray emitter exposed to the anisotropic radiation field of both accretion disks affects the gamma-ray opacity.

This project is an excellent opportunity for a student to get familiar with binary systems in the universe hosting one or two holes. The project has a descriptive part, where we will identify such systems and their properties. The computational part is based on already existing codes, which the student will learn to use.

#### References

- [1] Christie, D.R., "The morning glory of the Gulf of Carpentaria: a paradigm for nonlinear waves in the lower atmosphere", Australian Meteorological Magazine, 41, pp. 21-60, 1992.
- [2] Goler, R. & Reeder, M., Journal of Atmos. Sci., accepted. (available from Michael Reeder, Room 460).
- [3] Gottwald, G. & Grimshaw, R., "The formation of coherent structures in the context of blocking", Journal of Atmos. Sci., 56, pp. 3363-3678, 1998.

## Functional analysis tools for partial differential equations (P)

**Abstract:** Exact solutions to Partial Differential Equations can only be found in simple cases and/or when symmetries are involved. In the general case, we need to rely on mostly non-constructive methods to ensure the existence and uniqueness of solutions to these equations, and possibly to establish some of their qualitative properties.

A number of projects can be designed around Functional Analysis results and their usage in the study of Partial Differential Equations. A few examples include: Sobolev spaces, topological degrees, fixed points techniques, bootstrap methods (to establish the regularity of the solution), etc. The choice of a precise project will be done in discussion with the student.

## Numerical methods for diffusion equations in generic grids: design, analysis, implementation (P or A)

**Abstract:** numerous physical models, such as fluid flows models, lead to partial differential equations way too complex to be explicitly solved. Numerical schemes must be designed to get any practical information on the behaviour of the solution to the models. These schemes must be devised by taking into account engineering constraints, such as singularities in the model, the necessity to preserve certain quantities of interest (conservativity of fluxes), or the very generic and distorted meshes encountered in some applications.

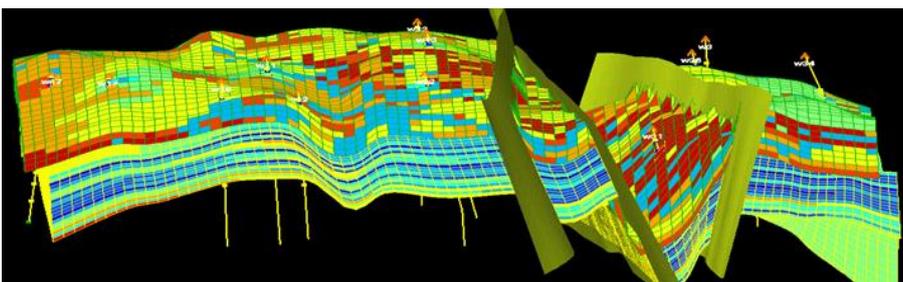
This project consists in studying one or more numerical schemes for diffusion equations: the historical Finite Volume method (with some structural limitations), more recent finite volume method, discontinuous Galerkin methods, and possibly higher order schemes. The focus will be on understanding the design of the methods and its properties, such as the respect at the discrete level of the coercivity or maximum principle enjoyed by diffusion PDEs. The design of each of these methods strongly relies on the theoretical properties of the equations so, depending on the interests of the student, the project might concentrate on the theoretical analysis of the methods (using discrete functional analysis techniques), or on practical implementations and comparison of the schemes. It is therefore suitable for students in pure mathematics who want to see how functional analysis can be adapted to the discrete setting of numerical schemes, as well as for the students in applied mathematics who want to increase their knowledge on modern numerical methods.

## Entropy solutions for hyperbolic equations (A, P)

Hyperbolic equations are systems partial differential equations which appear in a number of natural phenomena describing the evolution of fluids with very little viscosity (the air being an example). Given the complexity of fluid dynamics, it is no surprise if these equations themselves raise complex mathematical issues. These issues are already visible in the simplified scalar case, when we look at one equation and not a system of equations.

Two of these issues are (i) the possible non-uniqueness of the solution and (ii) the development of discontinuities (shocks) in the solution which prevents "classical" solutions from existing after some times. Mathematicians have struggled to find a rigorous formulation that would provide a proper framework to study these equations, i.e. a framework in which the solution exists and is unique.

The objective of this project is to understand this framework, which involves the notion of entropy solution. We will see why this notion of solution is a good one, and we will also look at its adaptation to more general equations involving, for example, boundary conditions or non-local (fractal) operators. The study of entropy formulations for hyperbolic systems of equations is also something we could consider



An example of a generic distorted mesh encountered in some applications.

## **Rostering staff with consideration of fatigue implications (A)**

Project Outline: Many organisations have to provide services around the clock and hence roster staff to work at all hours of the day. This can have significant impact on the level of fatigue. The resulting reduction in alertness can have significant implications particularly in health care and emergency services. This project will look at optimisation models and algorithms to generate rosters that are likely to reduce fatigue.

Some real world data is available to allow the student to work with realistic instances of such rostering problems. The project will involve looking at possible models for the fatigue implications of rosters and then develop optimisation methods to generate rosters that are better from this human perspective.

Pre-Requisites: Basic knowledge in programming is desirable, knowledge of Linear Programming, scheduling, heuristic algorithms is helpful but not essential

References:

- [1] Ernst, A. T., Jiang, H., Krishnamoorthy, M. & Sier, D. Staff scheduling and rostering: A review of applications, methods and models. *European journal of operational research* 153, 3–27 (2004).
- [2] Lodree Jr., E. J., Geiger, C. D. & Jiang, X. Taxonomy for integrating scheduling theory and human factors: Review and research opportunities. *International Journal of Industrial Ergonomics* 39, 39–51 (2009).

## **Lagrangian relaxation based decompositions of arbitrary integer programs (A)**

Project Outline: Lagrangian relaxation is a technique for removing “difficult” constraints in mathematical programs so that the problem decomposes into smaller subproblems or to ensure the remaining problem has a special structure that can be solved more efficiently. There are often multiple choices for mixed integer linear programs (MIP) of which constraints to relax and how to decompose the problem. This project will look at how to automate this process for arbitrary MIPs.

The decomposition can be shown to be equivalent to a k-partitioning in a hypergraph. Such problems are not easy to solve and this is only a pre-processing step for the computationally demanding task of solving the MIP. Hence efficient heuristic methods for this decomposition are essential. This project will develop a heuristic method for this decomposition and evaluate the effectiveness of this approach in obtaining Lagrangian bounds.

Pre-Requisites: Basic knowledge in programming is essential, knowledge of Linear Programming, heuristics or graph theory is helpful but not essential.

References:

- [1] Bergner, M. , A. Caprara, A. Ceselli, F. Furini, M. E. Lübbecke, E. Malaguti, and E. Traversi. *Automatic*
- [2] Dantzig–Wolfe reformulation of mixed integer programs. *Math. Program.* 149, 391–424 (2014).

## **Portfolio allocation and risk measures: which measure? (F)**

One of the main question in portfolio allocation is related to allocation investor's wealth across different assets for gaining highest profit in a specific time horizon. The earliest idea for this allocation was introduced by Markowitz in (1952). He proposed to maximize the returns according to some level of variance. The variance is controlling the amount of investor's risk. He optimized the allocation of wealth based on a constraint, i.e., a risk function.

After his pioneering paper, a lot of risk measures have been introduced. Surprisingly, to the best of our knowledge, there is no comprehensive empirical study to compare the performance of a portfolio allocation under all risk measures. Of course, there are some studies which only compare a few of them together.

The objective of this project is twofold: first, constructing a portfolio allocation strategy based on empirical regularities of financial time series such as heavy tails, asymmetry, and stochastic volatility. Second, provide a comprehensive empirical study of portfolio allocation for all existing risk measures such as standard deviation, value at risk, expected loss, expected shortfall, shortfall deviation risk, maximum loss, deviation entropic, and etc.

### Reference:

Markowitz, H. , 1952. Portfolio selection. *J. Finance* 7 (1), 77–91 .

Rachev, S. , Ortobelli, S. , Stoyanov, S. , Fabozzi, F.J. , Biglova, A. , 2008. Desirable properties of an ideal risk measure in portfolio theory. *Int. J. Theor. Appl. Finance* 11 (01), 19–54 .

## **Stochastic-deterministic hybrid modelling of reaction-diffusion processes in biology (A)**

Background: Describing spatially heterogeneous reacting systems mathematically is typically done with the use of the reaction-diffusion partial differential equation (PDE). In systems with sparsely distributed molecules the intrinsic stochasticity becomes important. These types of systems are the norm rather than the exception in intracellular environments, for example. In biology in particular, spatially heterogeneous reacting chemical systems are modelled using one of two approaches; compartment-based or molecular-based methods.

Molecular-based methods (often referred to as microscopic methods) trace the trajectories of all molecules in the system. Modelling a system in this way is only computationally possible if the copy numbers are very low but will provide the highest level of accuracy in a simulation. Compartment-based methods (often referred to as mesoscopic methods) discretise the domain into regions which are considered to be well-mixed. Diffusion is simulated by means of jumping events between compartments. Since it is only necessary to store the copy number per compartment, mesoscopic methods are much quicker but considered to be less accurate.

In order to deal with the complexity of biochemical systems, a vast number of hybrid methods have been proposed which utilise the most appropriate algorithm in various regions of the domain. The coupling technique has to be carefully constructed to join the modelling regimes seamlessly. This has been done in the case of coupling PDEs to molecular-based methods [1] and compartment-based methods to molecular-based methods [2] but not for PDEs and compartment-based methods.

The aim of this project will be to devise an accurate coupling algorithm for coupling a reaction-diffusion PDE with compartment-based simulation. The ultimate goal of this work would be to write an algorithm which would adaptively use the correctly modelling algorithm when and if it is needed within the domain for maximum efficiency and accuracy.

### References:

[1] Franz B, Flegg MB, Chapman SJ, Erban R (2012) Multiscale reaction-diffusion algorithms: PDE-assisted Brownian dynamics. *SIAM Journal on Applied Mathematics* 73(3): 1224-1247.

[2] Flegg MB, Chapman SJ, Erban R (2012) The two-regime method for optimizing stochastic reaction-diffusion simulations. *Journal of the Royal Society Interface* 9(70): 859-868.

## **Growing kidneys (A)**

How a single cell can undergo many generations of cell division and differentiation to create a fully functional human being at the moment of birth is a miracle as much as it is a mystery. Occasionally, the process is not completed properly. These congenital abnormalities can be devastating for the health of the future child. The most common anatomical site for congenital abnormalities is the kidney. The kidney, alongside other organs such as the heart and the brain, is essential to human life and many kidney abnormalities can be fatal.

In this project we will be generating theoretical and computational aspects of the morphology of kidneys in the developing embryo. We will be investigating how small changes in cellular responses to kidney forming stimuli may easily lead to severe congenital disorders. In particular, we will be interested in how the initial kidney precursor (the ureteric bud) is induced. Failure of this process to occur leads to kidney agenesis (and subsequent death of the individual).

The primary aim of this project is to develop a model of the developing ureteric bud. This may be done using a couple of different approaches continuum or discrete. A continuum approach would involve writing partial differential equations for inducing morphogens which allow for determination of the budding site on a one-dimensional domain. The discrete approach would be to make a cellular automaton simulation of budding process. The discrete approach would allow for significantly more complexity at the cost of tractability. The references [1,2] are good background reading to introduce kidney morphogenesis.

### References:

[1] M. Little, A. P. McMahon, "Mammalian Kidney Development: Principles, Progress and Projections", *Cold Spring Harb Perspect Biol*, 4:a008300, 2012

[2] F. Costantini, R. Kopan, "Patterning a Complex Organ: Branching Morphogenesis and Nephron Segmentation in Kidney Development", *Dev Cell Rev*, 18, 2010

## Uncrossing the signals of cancer (A)

In 1971, Richard Nixon declared war on cancer by signing the National Cancer Act. Over 40 years of intense worldwide fundraising and research later and cancer is still developed by one in three people and kills around one in five. Why is cancer such a difficult disease to eradicate? The answer is because cancer is not one disease: every cancer is different. Cancer is caused by a normal cell undergoing a mutation. This mutation can be any one of a many of mutations but the end result is the same. The cell starts to hallucinate: it perceives chemical signals which do not exist. If that signal is an instructional signal for the cell to divide (or to live longer than it should) the result is a tumorous growth.

In this project, we will be investigating a particular aberrant signal which is common to many cancers. This signal is usually propagated by "Wnt" proteins. In many cancers, cells behave as though they are receiving this signal when they are not and, as a result, multiply out of control. This is not the only by-product of aberrant Wnt signalling. Deregulation of the mechanism of Wnt signals in cancer leads to, or is a consequence of, internal dysregulation of proteins which are crucial for the normal function of other signals. The sequential breakdown of normal cellular behaviour allows the growth to be particularly malignant. This phenomenon in biology is known as signalling cross-talk. We will investigate the cross-talk mechanisms of Wnt. As there are a number of important cross-talks associated with Wnt, there is freedom to investigate that which is most interesting. Initially we will investigate these mechanisms using systems of ordinary differential equations but may then utilise spatial models (stochastic and deterministic) depending on the student's research interests. For a comprehensive background on the mathematical approaches used in the literature see Ref [1].

### References:

[1] B. Lloyd-Lewis, A. G. Fletcher, T. C. Dale and H. M. Byrne; "Toward a quantitative understanding of the Wnt/ $\beta$ -catenin pathway through simulation and experiment". *Wiley Interdiscip Rev Syst Biol Med.* 5(4):391-407 (2013).

## Discrete models of critical phenomena (P)

Background: Many probabilistic models defined on graphs possess special “critical” values of their parameters, at which long-range order develops and fractals emerge. Examples of such models include percolation, in which one studies the connectivity properties of random spanning subgraphs of some fixed graph, and the Ising/Potts models in which one studies random vertex colourings. The study of such “critical phenomena” has been a fertile area in mathematical physics for three quarters of a century. A wide variety of methods are used to study these models, ranging from rigorous combinatorial, algebraic and probabilistic methods, through to large-scale computer experiments and non-rigorous methods of theoretical physics. In the case of planar graphs, the conjectured conformal invariance of certain continuum limits of these discrete models has recently given rise to some very significant advances.

Project Outline: The project would start with a review of the required basic background in mathematical physics (statistical mechanics); the two references listed below being a good place to start. From there, a range of possible projects is available, and depending on your interests the project could include combinatorial, computational, and/or probabilistic aspects to a greater or lesser degree. There would be scope for an investigation that may lead to new results, particularly if the project involves computer experiments.

### References

- [1] Slade, G “Probabilistic Models of Critical Phenomena” in The Princeton Companion to Mathematics, edited by
- [2] T. Gowers, Princeton University Press (2008).
- [3] Grimmett, G “Probability on Graphs” Cambridge University Press (2010), available online free (legally) at <http://www.statslab.cam.ac.uk/~grg/books/pgs.html>.

## Markov-chain Monte Carlo methods in statistical mechanics (S)

Background: Statistical mechanics began life as a branch of mathematical physics, but is now a central paradigm for studying all manner of complex systems, across fields as diverse as physics, chemistry, biology, economics and sociology. An important branch of statistical mechanics concerns discrete models, in which one studies random structures defined on graphs. These studies have significant overlap not only with probability theory, but also combinatorics and computer science. Since models in statistical mechanics are often mathematically intractable, Markov-chain Monte Carlo (MCMC) methods have become an indispensable computational tool in this field.

However, not all Markov chains are created equal, and while two Markov chains may have the same stationary distribution (and therefore approximate the same statistical mechanical model), their rates of convergence to stationarity (and therefore their practical efficiency) can be very different. While the classical theory of Markov chains considers the late-time asymptotics of fixed chains, the relevant asymptotics in statistical mechanics concerns the growth of “mixing times” as the size of the state space becomes large. Quantifying the size of such mixing times, and designing new Markov chains with reduced mixing times, are the central tasks in this field.

Project Outline: The project would start with a review of the required basic background in discrete statistical mechanics, and Markov-chain Monte Carlo; the references listed below being a good place to start. From there, a range of possible projects is available, studying specific classes of Monte Carlo methods for specific classes of statistical-mechanical models. Depending on your interests, the project will involve a combination of both theoretical studies and computer experiments; the focus could range from being largely computational, to entirely theoretical. There would be scope for an investigation that may lead to new results.

### References

- [1] Levin, A, Peres, Y, and Wilmer, E “Markov Chains and Mixing Times”, available online free (legally) at <http://pages.uoregon.edu/dlevin/MARKOV/markovmixing.pdf>
- [2] Recorded lectures at <http://www.msri.org/web/msri/scientific/show/-/event/Wm406> and <http://www.msri.org/web/msri/scientific/show/-/event/Wm318>
- [3] Grimmett, G “Probability on Graphs”, Cambridge University Press (2010), available online free (legally) at <http://www.statslab.cam.ac.uk/~grg/books/pgs.html> .

## Modelling liquidity using Markov switching processes (F)

In financial markets, the liquidity of an asset or security refers to the degree to which it may be bought and sold in the market quickly without affecting its price. The classical assumption of perfect liquidity is quite far from reality. In practice, even the most liquid stock only has a finite number of shares on each of the "bid" (buyer) and "ask" (seller) sides. On the other hand, an illiquid stock regularly suffers from a shortage in its supply and/or demand, and often exhibits large gaps between the bid and ask prices.

The bid and ask prices are stored in what is known as a limit order book, which can be converted to a so-called supply curve (stock price as a function of volume traded). The project aims to model these supply curves using Markov regime-switching models, capturing the effects of large traders, the cost due to immediacy provisions and the varying states of economy. The impact of liquidity risk on derivative markets will also be examined.

References:

- [1] Çetin, U., Jarrow, R. A., & Protter, P. (2004). Liquidity risk and arbitrage pricing theory. *Finance and stochastics*, 8(3), 311-341
- [2] Mamon, R. S., & Elliott, R. J. (Eds.). (2007). *Hidden Markov models in finance* (Vol. 4). New York: Springer.

## Multilevel Monte Carlo Methods in Finance (F)

Monte Carlo simulation is a simple yet powerful numerical technique for computing the expectations of random variables. In its most basic form, the method simulates many sample paths of a mathematical model and estimates the required expectations by computing averages. It is a popular method used in many areas of mathematics and statistics, including financial mathematics where it is frequently used in options pricing, portfolio selection and risk management. Monte Carlo simulations are easy to implement and have the flexibility to handle extremely complex models. The main disadvantage is its rate of convergence, where a large number of sample paths may be required for good accuracy.

The seminal work of Giles [1] introduced the notion of a multilevel Monte Carlo simulation. The term "multilevel" refers to the fact that several simulations are carried out under different levels of model discretisation, ranging from coarse to fine. For example, the model discretisation could be referring to the size of each time step for a stochastic process. The required expectation is first roughly computed at the lowest simulation level with the coarsest discretisation, and then gradually improved by adjusting for the incremental differences between adjacent simulation levels. When performed correctly, this method of iterative refinement converges much faster than traditional Monte Carlo methods in terms of computational time.

In this project, we will study the application of multilevel Monte Carlo to problems in financial mathematics. Specifically, we will apply it to the pricing of path-dependent options as well as use it to solve stochastic control problems arising from portfolio selection and utility maximisation.

- [1] Giles, M. B. (2008). Multilevel monte carlo path simulation. *Operations Research*, 56(3), 607-617.
- [2] Belomestny, D., Schoenmakers, J., & Dickmann, F. (2013). Multilevel dual approach for pricing American style derivatives. *Finance and Stochastics*, 17(4), 717-742.
- [3] Giles, M. B., & Reisinger, C. (2012). Stochastic finite differences and multilevel Monte Carlo for a class of SPDEs in finance. *SIAM Journal on Financial Mathematics*, 3(1), 572-592.

## Machine Learning in Stochastic Control Problems (S)

A stochastic control problem is an optimisation problem in which an agent tries to maximise an objective function by controlling some aspects of an underlying stochastic process. A simple example is in portfolio optimisation (Merton's portfolio problem), where an investor must decide on how many units of stock to hold at any time in order to maximise their expected utility. Since the stock price movements are random, the wealth of the portfolio is a stochastic process. The composition of the portfolio can change over time and depend on the history of the stock price movements.

In most cases, stochastic control problems do not have simple analytical solutions. Hence numerical methods are required. One popular approach is to apply the dynamical programming principle (similar to backward induction) and reformulate the problem as a particular class of partial differential equations (PDE) known as the Hamilton-Jacobi-Bellman equations, and then solve these equations using various existing numerical methods for PDEs. Another approach is to simulate the trajectories of the stochastic process under randomised controls, then approximate the optimal control via least squares regression.

In recent times, machine learning techniques have gained immense popularity in numerous fields. They have shown to be effective in solving many approximation, prediction and decision making problems in complex models. In this project, we aim to study the application of machine learning techniques in stochastic control problems, ranging from simple regression and classification algorithms to the more complex methods such as reinforcement learning. This project has applications in optimal stopping problems, stochastic differential games, robust finance and optimal transport.

References:

- [1] Merton, R. C. (1969). Lifetime portfolio selection under uncertainty: The continuous-time case. *The review of Economics and Statistics*, 247-257.
- [2] Kharroubi, I., Langrené, N., & Pham, H. (2014). A numerical algorithm for fully nonlinear HJB equations: an approach by control randomization. *Monte Carlo Methods and Applications*, 20(2), 145-165.
- [3] Li, Y., Szepesvari, C., & Schuurmans, D. (2009, April). Learning exercise policies for American options. In *Artificial Intelligence and Statistics* (pp. 352-359).

### **Fourier restriction estimates (P)**

Fourier restriction estimate is one of the core topics in harmonic analysis. In 1960s, E. M. Stein observed for the first time the restriction phenomenon of the Fourier transform, and proposed the Fourier restriction conjecture. This conjecture in 3 and higher dimensions is still open and has been studied extensively. Besides revealing a fundamental property of the Fourier transform, Fourier restriction estimate has found tremendous applications in other fields, e.g. PDEs. This project will be devoted to study the classical Fourier restriction results and its applications in PDEs, providing a friendly introduction to the fascinating world of analysis and PDEs.

### **$L_p$ eigenfunction estimates on compact manifold (P)**

This project will be devoted to the study of  $L_p$  estimates for the eigenfunction of the Laplacian operator on compact manifold. These estimates are fundamental and have been the one of main topics in the field of analysis and geometry. Through this project, you will play with tools from analysis, geometry and dynamical system.

### **Some topics in nonlinear dispersive equations (P)**

In the last 30 years, there were enormous developments in the fields of nonlinear dispersive equations, e.g. KdV, Schrodinger and wave equations. Many new tools were developed and new ideas from other fields have played important roles. This project will focus on one of the following topics: low regularity well-posedness problems, long-time behaviour, blow-up behaviour, and probabilistic well-posedness.

### **3D axisymmetric Navier-Stokes equation (P)**

The global existence of the large smooth solution for the 3D Navier-Stokes equation is a long-standing open problem. It is one of the millennium-problems. This project will focus on the axisymmetric case. This case was known to have some more structures so that there are rich results. Especially recently the criticality for this special case was revealed by Lei-Zhang basing on the work of Chen-Fang-Zhang. Their results showed it is only logarithmically far to finally solve the problem for this case. This project will be devoted to study the classical results, the rich structure as well as the recent mentioned works.

## Topics in dynamical Systems (P)

Background: If we know exactly what happens to a system under tiny changes of time, can we use this information to determine the long term behaviour of the system? This question is at the heart of dynamical systems research. The development of chaos theory shows that many systems which are highly predictable at small times are completely unpredictable over the long run. Nevertheless, many dynamical systems have invariant objects which are unchanged throughout time and aid greatly in understanding the overall qualitative behaviour of the system.

Project outline: This project will look at understanding the behaviour of certain families of dynamical systems based on invariant properties of the systems.

References:

- [1] A. Katok, B. Hasselblatt, Introduction to the modern theory of dynamical system.
- [2] D. Ruelle, Elements of Differentiable Dynamics and Bifurcation Theory

## Topics in ergodic theory (P)

Imagine a billiard table, either rectangular or a more complicated shape with many straight or curved edges, but with no pockets for a ball to fall into. Then imagine a friction-less ball forever moving across the table and reflecting off of the walls. Does this ball visit all regions of the table? Does it favour some areas of the table over others? These questions, relating how one path through a space compares to the average behaviour over all points, define the notion of “ergodic theory.” This field uses measure theory to accurately describe the average behaviour of very chaotic dynamical systems. The study of billiards is just one example of its application.

Project outline: This project will begin with the study of invariant measures, ergodicity, mixing, and other related concepts. From there, further work could include the study of certain types of dynamical systems and determining when ergodicity and related properties hold.

References:

- [1] P. Walters, An introduction to ergodic theory
- [2] A. Katok, B. Hasselblatt, Introduction to the modern theory of dynamical system.
- [3] D. Ruelle, Elements of Differentiable Dynamics and Bifurcation Theory

## Numerical simulation of multiscale systems (P)

Multiscale or “slow-fast” systems are dynamical systems in which different parts of the system evolve at vastly different scales of time. As an example, cloud cover over a region of the Earth changes from minute to minute, but large scale changes in climate can occur over decades or longer.

Numerical simulation of dynamical systems requires calculating the state of system from one instance of time to the next, and in a multiscale system there is no good choice of time step which ideally fits both the slow and fast dynamics.

This project will try to quantify the error in numerically simulating such systems, compare various techniques, and examine the effect of the floating-point precision of computer implementations of the algorithms.

References:

- [1] E. Hairer, S. P. Nørsett, and G. Wanner. Solving ordinary differential equations I.
- [2] P. Henrici. Discrete variable methods in ordinary differential equations.

## **Financial mathematics (F)**

(co-supervised with Prof Fima Klebaner)

Project Outline: There are many topics to choose from. Topics vary greatly in the degree of theoretical and practical work involved. Students can choose a topic with any mixture of the theory of stochastic calculus (used in the modelling of financial markets), and the practice of statistical analysis (applied to real data from the Australian market).

References

[1] Hull, J., "Options, futures and other derivative securities", Prentice Hall, 1989.

[2] Klebaner, F.C., "Introduction to stochastic calculus with applications", Imperial College Press, 1998.

## **Characterisations and probability distributions (S)**

Project Outline: The normal and exponential distributions play essential roles in probability and statistics. This project aims at reviewing the main characterisation results and how these are used in various areas of probability and statistics.

References

[1] Galambos, János & Kotz, Samuel, "Characterizations of probability distributions: a unified approach with an emphasis on exponential and related models", Springer-Verlag, 1978.

[2] Patel, J.K. & Read, C.B., "Handbook of the normal distribution", Dekker, 1996.

## **Probability, a measure theory approach (S)**

Project Outline: Probability (or stochastic) models are very widely used. A good understanding of the basic probability theory is an absolute necessity. This topic will cover the basic measure theory (measurability, integrability ...) as well as concepts specific to the area of probability theory (independence, conditioning, distributions...).

## Topics in graph decompositions and combinatorial designs (P)

Background: Combinatorial design theory is an area of mathematics that studies arrangements of objects that are in some sense “balanced”. It has applications to the design of experiments, to coding and cryptography, to traffic grooming in networks, and to numerous other areas. Many problems in combinatorial design theory can be considered as problems concerning decomposing graphs into edge-disjoint subgraphs, and this way of viewing them has led to many important results and insights.

Objectives: This project will involve investigating one the many easily accessible problems in the area of graph decompositions and combinatorial designs. Possible problems could concern

- embedding Steiner triple systems;
- colouring graph designs;
- resolutions of Steiner triple systems;
- decompositions of graphs into cycles; or
- infinite designs.

Expectations: A reasonable degree of mathematical maturity.

Assumed Knowledge: None.

Reading: To be determined depending on the specific problem considered.

### **Statistical identification of non-protein-coding RNAs involved in human phenotypes and disease (S)**

Project Outline: The human and other genomes contain many regions for which there is evidence of a functional role but which do not code for proteins. Although some of these non-protein-coding genes have been characterised, many more remain poorly understood. One technique for learning about such genes is multiple change-point analysis. In this technique, a genome or a multiple alignment of genomes is divided into segments that are internally homogenous with respect to one more properties characteristic of function, but differ from neighbouring segments with respect to those properties. This project will explore new methods of multiple change point inference and will apply them to identify new non-protein-coding functional elements in genomes, with a particular emphasis on RNAs involved in human phenotypes and diseases.

### **Learning about genes using Bayesian classification (S)**

Project Outline: The human and other genomes contain many regions for which there is evidence of a functional role but which do not code for proteins. Although some of these non-protein-coding genes have been characterised, many more remain poorly understood. One technique for learning about such genes is to organize them into classes of similar or related sequences, so that knowledge about one member can illuminate other members of that class. This project will explore methods of classifying such genes, and ways of using such classifications to expand knowledge.

### **Detecting DNA motifs that drift (S)**

Project Outline: DNA motifs are short patterns in DNA sequences that play a functionally important role. Recent studies have found that the ability to detect such motifs is enhanced using new algorithms that combine data from multiple species. However, these algorithms require motifs to remain similar over evolutionary time, and do not allow for motifs that change with time (drift). This project will trial several new statistical methods for detecting motifs that drift.

### **Modelling DNA evolution under biological constraint (S)**

Project Outline: Many functional parts of the genome, including non-protein-coding RNAs, are not free to evolve neutrally, but are constrained by the need to maintain their function. This project will involve developing new statistical models for evolution of biological sequences under such constraints. One use of such models is to identify parts of genomes that are evolving under constraint, and which are therefore likely to be functional. Another use is to enhance phylogenetic algorithms (that is, algorithms that estimate the evolutionary tree of a set of sequences). A particular focus will be on new Bayesian methods for investigating ephemeral conserved elements in eukaryotic genomes. These are functional elements that are conserved for time-periods too short to be detected in most comparative genomics approaches. This topic has the potential to identify new forces and mechanisms of genome evolution and gene regulation.

### **Associations between phenotypes and biological networks (S)**

Project Outline: A phenotype is an observable biological characteristic of an individual organism. Although some phenotypes are determined by a single genetic locus or gene, many are the result of contributions from multiple loci. It is likely that many of the loci that contribute to a particular phenotype will belong to the same biological network or system. This project aims to exploit this supposition by identifying statistically significant associations between phenotypes and genetic variations within the member genes of a biological network.

## **Modelling the spread of invasive pest species (S)**

Fire ants were accidentally introduced in the Brisbane area over a decade ago, and intensive efforts to eradicate them are still ongoing. Bayesian probabilistic models of the spread of these ants were developed and are influencing eradication efforts. In this topic, the student will look at ways to generalise the models for other invasive pest species. This topic has the potential to enhance protection of Australia's ecosystems by providing better statistical models and methods for predicting the spread of invasive species.

## **Bayesian adaptive Markov chain Monte Carlo methods (S)**

Project Outline: Markov chain Monte Carlo (MCMC) is an important technique in applied Bayesian statistics, and is used to draw a sample from a posterior distribution, in order to estimate the marginal distributions of a parameter of interest. Designing an efficient MCMC sampler for a complex inference problem is often difficult. In this project, the student will investigate new methods for adapting an MCMC sampler to improve efficiency, using a Bayesian framework to aid in selecting the parameters of the sampler.

## **Correlating training practices to injury prevention in sports (S)**

Project Outline: This project will develop novel Bayesian statistical methodologies for the analysis of longitudinal data when a significant proportion of the data is missing, and may not be missing at random. The methods will be applied to sporting injury data sets and used to guide the development of training practices that minimise the risk of injury. A specific approach will be the investigation of popular non-Bayesian data imputation techniques known as "hot deck" and "cold deck" approaches and their potential for incorporation within a Bayesian framework. The "hot deck" approach involves imputing data from a randomly selected similar record within the given data set, whereas the "cold deck" approach involves selecting donor records from another data set. In both cases, a Bayesian approach provides a natural way to incorporate uncertainty about the imputations into the resulting inference.

## **Use of alternative statistical analysis methodology to improve variance estimates on vehicle secondary safety ratings (S)**

(co-supervised with Dr Stuart Newstead – Monash University Accident research Centre)

A key area of Monash University Accident Research Centre research is producing ratings of relative vehicle safety from the analysis injury outcomes of real world crashes. A critical aspect of the ratings being useful for consumer information is producing ratings that are as accurate as possible. Accuracy of the ratings is reflected by confidence limit widths on the ratings estimates with the general aim being to make the confidence limits as narrow as possible. Current methodology uses asymptotic estimates of rating variance. The general aim of this project is to assess the potential use of these alternative methodologies to producing ratings estimates and to assess the benefits they offer over the current techniques in improving estimation accuracy.

## **A study of impact severity proxies used in vehicle safety ratings (S)**

(co-supervised with Dr Stuart Newstead – Monash University Accident research Centre)

Crash impact severity is known to be a key factor determining injury outcome in a crash. Whilst impact severity is available in in-depth crash inspection databases such as the Australian National Crash In-depth Study, impact severity is never available in police reported crash databases such as those used to estimate the Monash University Accident Research Centre's vehicle safety ratings. Work completed under a European Commission funded project reviewed the performance of vehicle secondary safety rating systems in use internationally against a theoretical framework and using data simulation techniques. The review found the methods used to estimate the

Australasian Used Car Safety Ratings performed particularly well compared to all other methods reviewed. However, it noted that the ultimate accuracy of the Australasian method in reflecting underlying vehicle secondary safety relied on the ability of a number of proxy measures of crash impact severity to represent the real underlying crash impact severity that is not available in the data. Currently, the Australian ratings systems use driver age and gender, speed zone and number of vehicles involved as proxy impact severity measures.

The proposed project aims to assess the performance in representing underlying impact severity of the current proxy measures used in the Australasian ratings system. It aims to achieve this through analysis of in-depth crash inspection data found in ANCIS and its predecessor databases. ANCIS data contains a measure of impact severity as well as data on the proxy measures used in the UCSRs. A further aim of the project will be to assess whether there are other data fields in the police reported crash databases that can potentially improve the representation of impact severity in estimating the ratings. A potential outcome of the project will be a validation of the current impact severity proxy variables used in estimating the ratings. Conversely, the project will provide indications on how use of the proxies can be enhanced to produce ratings that provide an even fairer comparison between different vehicle models by controlling further for impact severity differences between vehicle models.

### **Models and methods for spatially correlated time series (S)**

Project outline: Spatially correlated time series arise in many contexts, including monitoring of water quality, disease outbreaks, species range distributions, cellular drug responses, and many more. Statistical modelling of such phenomena can involve high-dimensional models for which parameter inference can be difficult. This project will investigate novel Markov chain Monte Carlo methods for problems of this type.

## Large deviations theory and applications (S)

(co-supervised with Dr Andrea Collevocchio)

The project focuses on the Large Deviations Theory and its application to find the most likely paths a stochastic system (a dynamical system with noise) can take. The project involves studies in probability, optimality and differential equations. Application can be in physics, biology or finance. This project will suit a strong mathematically minded student in probability.

References:

- [1] Amir Dembo , Ofer Zeitouni, “Large deviations techniques and applications” Second ed., Springer-Verlag, New York, 1998
- [2] M. I. Freidlin and A. D. Wentzell, “Random perturbations of dynamical systems”. Second ed., Springer-Verlag, New York, 1998
- [3] F. Klebaner and R. Lipster, “Asymptotic analysis of ruin in the constant elasticity of variance model theory” Probab. Appl. Vol. 55, No. 2, pp. 291–297.

## **Applications of optimal transport to model calibration in finance (F)**

The problem of optimal transport was first considered in the context of civil engineering where materials must be transferred from one site to another while minimising transportation costs. Informally the problem is as follows: given two spatial distributions of mass, one wants to displace the first onto the second, while minimising a cost function. In recent years, theories in optimal transport as well as related variational problems have attracted considerable interests from leading mathematicians, offering an impressive range of applications, in fluid dynamics, plasma physics, image reconstruction, and economics.

The project aims to apply the technique of optimal transport to financial mathematics, specifically in the problem of volatility calibration. In financial markets, the underlying volatilities of risk assets are commonly modelled using local volatility and stochastic volatility models which require calibration. The probability distributions of the asset prices can be inferred from observed option prices at a set of fixed maturities. However, the behaviours and distributions of the asset prices between those fixed maturities are unknown, and this is where optimal transport can be applied. Numerical techniques from the theory of optimal transport will be developed and implemented to solve local volatility calibration problems.

### References:

- [1] Benamou, J. D., & Brenier, Y. (2000). A computational fluid mechanics solution to the Monge-Kantorovich mass transfer problem. *Numerische Mathematik*, 84(3), 375–393.
- [2] Dupire, B. (1994). Pricing with a Smile. In *Risk Magazine*.

## Planar Brownian motion and complex analysis (S)

Project outline: There is an intimate connection between planar Brownian motion and complex analysis, and the major theme of this project will be to tackle problems which lie in the intersection of these two topics. To be specific, a holomorphic map applied to a Brownian motion yields a new stochastic process which can be realized as a Brownian motion run at a variable speed. This connection can be used to motivate and provide proofs of many of the major results in complex analysis; conversely, this conformal invariance, as it is often called, can also be used to prove many interesting results on planar Brownian motion via complex analytic techniques. We will study these techniques in more detail and look for deeper connections.

## Random walks and electrical resistance on graphs (S)

Background: There is a beautiful and well-known connection between the properties of electricity in a circuit and the properties of a walker moving randomly amongst the vertices of a graph. An excellent source concerning this is Doyle and Snell's book, given in the references. In order to be able to make use of this, it is convenient if the graph or circuit in question possesses some degree of symmetry. For infinite graphs it is therefore logical to study objects such as grids, and for finite graphs it is logical to study particularly regular graphs, such as the distance-regular graphs.

Objectives: The first step will be for the student to thoroughly understand the material presented in the references. From there, we may move in a number of directions, depending on the underlying interest of the student. For example, with a student interested in physics or random processes we may consider some deeper aspects of the problems concerning grids, whereas for a student interested in combinatorics we may concentrate on distance-regular graphs.

Expectations:

- Understanding the material in the references.
- Writing some computer code in order to make and test conjectures.
- Conjecturing and proving some new results, be they publishable or not.

Assumed Knowledge: Some basic probability and/or combinatorics would be helpful, but is not essential.

Reading:

[1] Doyle, P. and Snell, J. 1992 Random Walks and Electric Networks, MAA.

[2] Biggs, N. 1993 Potential theory on distance-regular graphs. *Combinatorics, Probability and Computing* 2, p. 243-255.

[3] Biggs, N. 1997 Algebraic Potential Theory on Graphs, *Bulletin of the London Mathematical Society*, Volume 29, Number 6, p. 641-682.

## Percolation (S)

Background: In the last few decades, percolation has become one of the hottest topics in probability theory. To put it simply, suppose that in a given graph we remove each of the edges with a fixed probability  $p$ . We then may ask about the probability of moving from one side of the graph to the other or from one point to another, using only the remaining edges.

Objectives: The student must first understand the basics of this subject, and then we will decide together how to proceed. A student with a solid background in complex analysis may be interested in learning about a recently discovered connection between percolation and conformal mappings, called SLE. With a student more interested in combinatorics, however, we may study this process on finite graphs.

Expectations:

- Understanding the prerequisite material.
- Writing computer code in order to understand existing theorems.
- Looking at some problems involving the future direction of this field.

Assumed Knowledge: Basic probability theory. Some complex analysis would also be useful.

Reading:

[1] Grimmett, G. 1999 Percolation, Springer.

## **Complex analysis (S)**

The exact project is to be decided in consultation with Greg Markowsky taking into consideration your personal interests and mathematical background.

## Knot theory and group representations (P)

Project outline: This project would start with some background on knot theory and 3-dimensional topology. We will then investigate the fundamental groups of various knots and their representations. The project could then continue to investigate objects such as character varieties, A-polynomials and coloured Jones polynomials.

References:

- [1] Colin Adams, The Knot Book
- [2] Dale Rolfsen, Knots and Links

## Low-dimensional contact topology (P)

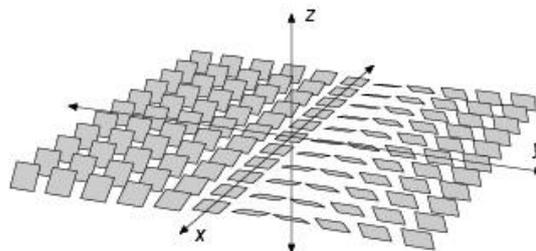
Background: The study of low-dimensional (2- and 3-dimensional) topological spaces is central to much science and mathematics, from cosmology and string theory to complex analysis and differential geometry. Contact geometry, a type of geometry related to classical mechanics, has in recent times provided a great deal of insight into 3-dimensional topology, with some fascinating connections to the topology of surfaces.

Project outline: This project would start with developing sufficient background on low-dimensional contact topology. Several directions are then possible, including the following:

- Open book decompositions and contact structures
- Characteristic foliations and dividing sets
- Knots in contact 3-manifolds

References:

- [1] Hansjorg Geiges, An Introduction to Contact Topology



## Topics in symplectic geometry (P)

Background: Classical Newtonian mechanics was reformulated in the 19th century by William Hamilton. The mathematical language of Hamiltonian mechanics is symplectic geometry. This beautiful subject encompasses much of classical physics, but has also enjoyed several breakthroughs in recent years, connections with string theory, and the development of powerful invariants.

Project outline: This project would begin with a study of symplectic vector spaces, which are the building blocks of symplectic geometry, and symplectic manifolds. From there, several directions are possible, depending on the interests of the student, such as:

- Reformulating various physical theories (mechanics, optics, electromagnetism) in terms of the mathematics of symplectic geometry
- Dynamical systems in symplectic geometry
- Holomorphic curves, Floer homology and Gromov-Witten theory

References:

- [1] Stephanie Singer, Symmetry in Mechanics
- [2] Dusa McDuff and Dietmar Salamon, Introduction to Symplectic Topology

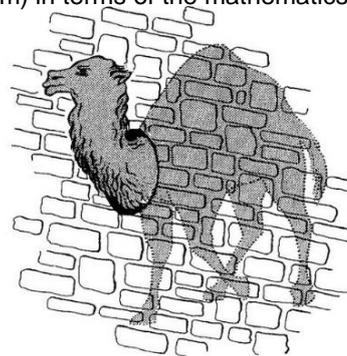


FIG. 1.3. The symplectic camel

## Topological quantum field theories (P)

Background: Quantum field theory describes our universe at a fundamental level, but it is plagued with difficulties. One approach mathematicians have taken is to define Topological Quantum Field Theories, or TQFTs, which are rigorously defined mathematical theories but possess some of the properties of quantum field theory. The mathematics that arises has fascinating connections to several branches of geometry and algebra.

Project outline: This project would start with a review of some necessary topology and algebra. Several projects are then possible, depending on the interests of the student, such as:

- Classification of low-dimensional TQFTs
- Khovanov homology, a powerful method for distinguishing knots based on TQFT ideas
- Relationship to mathematical physics, matrix integrals and quantum groups
- TQFT arising from contact and symplectic geometry

References:

[1] Joachim Kock, Frobenius Algebras and 2D Topological Quantum Field Theories

[2] Daniel Mathews, Itsy Bitsy Topological Field Theory, <http://arxiv.org/pdf/1201.4584v2>

## Application of stochastic portfolio theory on ASX 200 (F)

The dynamics of stocks are known to be affected by their corresponding market-cap. The study of this effect gave birth to stochastic portfolio theory in 2002 by Robert Fernholz. In stochastic portfolio theory, a portfolio is considered as a function from market cap to investment weight. The surprising fact is that, under weak assumptions, one may construct the portfolio based only on their market caps without a short position that performs better than market-weighted index ETFs in a long term. This mathematical result has been proved to be true for historical US stock data. Unfortunately, most of the analysis has been restricted to US Stock markets.

The aim of the project is of two folds. The first part is to apply stochastic portfolio theory on the members of ASX 200 (The biggest 200 Australian Stocks) and inspect their performance compared to ASX 200. Various types of portfolio generated from market caps will be investigated. The second part is to incorporate transaction cost to stochastic portfolio theory. In the real world, due to transaction cost, there is a trade-off between theory and practice. If one tries to follow the theoretical optimal portfolio, he/she will need a large number of trades and will have to pay a large amount of money as the transaction fee. If one slowly follows the optimal portfolio, then his/her strategy will not be optimal.

The project contains both theoretical and empirical aspects. First of all, the project requires the understanding of probability theory, stochastic calculus, and stochastic optimization to study stochastic portfolio theory. In addition, since we want to apply the mathematical models to the real-world data, the project requires to obtain market data (Bloomberg Terminal), manipulating big data (JSON formatted), and other numerical techniques.

Reference:

[1] Fernholz, E. Robert. "Stochastic portfolio theory." *Stochastic Portfolio Theory*. Springer, New York, NY, 2002.

[2] Karatzas, Ioannis, and Robert Fernholz. "Stochastic portfolio theory: an overview." *Handbook of numerical analysis*. Vol. 15. Elsevier, 2009.

## Backward stochastic differential equations and stochastic optimization of marked point processes (S)

Backward stochastic differential equation (BSDE) is introduced by Bismut (1973) as a dual problem of stochastic control. Since then, BSDE has been one of the main tools to study stochastic optimization of a dynamical random system. One of the most frequently found dynamical random systems is the network such as SNS, or disease spreading. The dynamic random network can be seen as a multidimensional point process if one considers each edge as a point process (1 if connected, 0 if disconnected). The BSDE approach is desirable for controlling dynamic random network.

This project aims to develop a BSDE framework for a general optimizing problem of multidimensional point processes with a finite number of states. Our control will be the stochastic intensities on a restricted subset of point processes and our reward function is a functional on the path of point processes. The numerical methods for application will also be developed and implemented to a few toy examples.

Reference

[1] Confortola, Fulvia, Marco Fuhrman, and Jean Jacod. "Backward stochastic differential equation driven by a marked point process: an elementary approach with an application to optimal control." *The Annals of Applied Probability* 26.3 (2016): 1743-1773.

[2] El Karoui, Nicole, Shige Peng, and Marie Claire Quenez. "Backward stochastic differential equations in finance." *Mathematical finance* 7.1 (1997): 1-71.

### Isoperimetric surfaces in geometry (P)

Background: Isoperimetric surfaces are surfaces that minimize area subject to a volume constraint. They arise naturally in calculus of variation and provide a natural tool to attack some basic geometric problems.

Possible project topics under this area include:

- Review Hubert Bray's approach to Volume Comparison using isoperimetric surfaces techniques.
- Investigate potential applications in the study of manifolds with boundary.
- Review Gerhard Huisken's approach to the definition of quasi-local mass via isoperimetric surfaces in general relativity.

### Newtonian limit and Post-Newtonian expansions (P)

Background: The Newtonian limit is the study of solutions to Einstein gravity coupled to matter in the limit that  $v/c \rightarrow 0$ , where  $v$  is a characteristic velocity scale associated to the gravitating matter and  $c$  is the speed of light. In this limit, one expects that solutions of general relativity approach solutions of Newtonian gravity in some sense.

Starting from a fully relativistic solution with a well-defined Newtonian limit, one can try and expand the solution in powers of  $v/c$ . The resulting expansion is known as the Post-Newtonian expansion. This produces a sequence of equations beginning with the Newtonian gravitational one. These equations can be solved to yield an approximation to the fully relativistic solution to a certain order in  $v/c$  for  $v/c$  sufficiently small.

Possible project topics under this area include:

- (numerical) In general, there will be a critical time  $T_c$  after which the Newtonian solution or more generally the Post-Newtonian expansions will no longer be a valid approximation to the fully relativistic solution. The aim of this project would be to solve the spherically symmetric Einstein equations coupled to a perfect fluid and try to identify the critical time  $T_c$  for specific classes of initial data.
- (analytical) In the physics literature, Post-Newtonian expansions are computed using formal expansions without any rigorous justification. Recently, I have, using PDE techniques, established the validity of the Post-Newtonian expansions in the so called near zone. The goal of this project would be to try and understand the relationship between the formal expansions used in the physics literature and the rigorous expansions I obtained using PDE techniques.

### Renormalization group flow (P)

Background: The Renormalization Group (RG) flow arise from demanding cut-off independence of classical field theory quantization. For the special case of nonlinear sigma models, the RG equations correspond to geometrical flow equations for a Riemannian metric on a manifold. In general, the RG equations are extremely complicated. However, they do depend a small parameter and are often studied by expanding in the parameter and truncating at a certain (loop) order.

Possible project topics under this area include:

- (analytical) Ricci flow appears as the approximation to RG flow at the one-loop level for the non-linear sigma model. The aim of this project would be to carefully understand this relationship between RG and Ricci flow.
- (analytical) Entropies are important quantities for understanding the behaviour of RG flow. The goal of this project would be to interpret the Perelman's entropy for Ricci flow in terms of an entropy for the full RG flow.
- (numerical) In spherical symmetry, solve numerically both the first and second order RG equations. The goal of this project would be to identify regions in space-time where the first and second order RG equations are qualitatively the same and also where they differ significantly.
- (analytical) The aim of this project would be to extend existing work on spherically symmetric Ricci flow to prove either global existence or singularity formulation of solutions to the second order RG equations.

## Prescribed mean curvature surfaces (P)

Background: Soap films and soap bubbles are examples of surfaces of constant mean curvature. The mathematical equations describing them are non-linear, second order, elliptic partial differential equations. Other examples of prescribed mean curvature are capillary surfaces and also maximal hypersurfaces in relativity. There is extensive literature, covering different mathematical approaches for proving existence, regularity and obtaining information on the shapes of such surfaces.

Possible projects:

- Isoperimetric property of the sphere
- Delaunay surfaces (classification of axially symmetric constant mean curvature surfaces)
- Existence of solutions (either by classical partial differential equations methods, or measure theoretical ones)
- Gradient estimates (classical partial differential methods)
- Construction of minimal surfaces - Weierstrass representation
- Construction of minimal surfaces - geometric heat flow methods
- Construction of maximal hypersurfaces in spacetime – apriori estimates: general relativity.

## Discretely self-similar (DSS) singularities (P)

Background: Motivated by the pioneering analysis of the spherically symmetric Einstein equations with massless scalar field matter by Demitri Christodoulou, around 1990 Choptuik discovered numerically that spacetimes at the borderline of forming a black hole, instead developed a naked singularity with a new and totally unexpected structure. One critical issue is to discover whether this DSS singularity is a true (non-removable) singularity or not. Numerical evidence suggests that it is removable, but this evidence is not conclusive and may be numerical artefact.

Possible projects:

- (numerical) solve the resulting 1+1 Einstein-massless scalar field PDE, using Choptuik's adaptive mesh refinement;
- (numerical) solve the 1+1 hyperbolic PDE using Stewart's (1996) double null formulation;
- (numerical) Find the underlying DSS solution to high accuracy, using Gundlach's Fourier expansion;
- (analytic) Prove the existence of the DSS solution using Gundlach's technique;
- (analytic) Review Christodoulou's proof of global existence for the Einstein-massless scalar field equations, and the proof that some initial data can evolve to create a black hole;
- (analytic or numerical) Study similar questions for the case of massive scalar field, with or without electromagnetic charge, or for the Einstein-Yang-Mills equations.

## Spacetime energy (P)

The proofs of the Positive Mass Theorem by Schoen and Yau (1979) and Witten (1981) formed a watershed in the application of mathematical techniques to the Einstein Equations. The two proofs are quite different and their inter-relationship is still far from understood. The Schoen-Yau proof uses quasi-linear elliptic PDE, minimal surface theory and differential geometry; the Witten proof uses spinors and existence of solutions to the elliptic Dirac equation.

Possible projects:

- Review the Schoen-Yau proof of the PET and the related Positive Mass Theorem, which incorporates the linear momentum of the spacetime;
- Study the use of special foliations (polar coordinates) in partial proofs of the PMT based on monotone functionals, in particular the relation between the Hawking mass and the Geroch inverse mean curvature flow;
- Review properties of spinors and the Witten proof of the PMT.
- (Numerical) Solutions of the initial 3D spatial geometry may be constructed by solving a parabolic equation. This project will construct such solutions numerically to study their geometry.

## The bathtub vortex (A)

Background: It is a common myth that the direction of rotation of bath water as it drains down a plughole is determined principally by the rotation of the Earth – in particular the hemisphere in which it is performed. Careful experiments have been performed to confirm that the rotation of the Earth has only a miniscule effect on the motion (Shapiro, 1962; Trefethen et al, 1965) and that can also be demonstrated theoretically using simple scaling arguments. More recently, Andersen et al (2003, 2006) and Tyvand & Haugen (2005) published experimental and computational studies of the problem and demonstrated that the influence of the rotation of the Earth is negligible. Foster (2014) also presents an asymptotic linearised theory for the motion that is consistent with their results. But why does the water so often flow down the plughole in a consistent direction, and why is that direction opposite in the Australia to what is commonly observed in the United Kingdom, for example?

Objectives: The project will review previous analytical, experimental and computational work on this problem for simplified geometries. Among other things, this will help identify the principal determinants of the direction of motion of the fluid at the outlet and assist in identifying the key physical principles based on a mathematical analysis of the equations of motion.

Expectations:

- undertake a thorough review of existing primary literature sources on this problem;
- identify the dominant forces that affect the fluid motion, derive the corresponding governing equations and assess the relative size of the relevant nondimensional parameters;
- simplify and solve the equations in appropriate cases, as described in previous studies;
- consider whether one simplified model that can adequately represent the phenomenon;
- develop a simple computational model for axisymmetric free-surface flow in a cylinder;
- undertake some simple computational experiments.

Assumed knowledge: MTH3011, MTH3051 and MTH3360

Reading:

- [1] Andersen A. et al, Anatomy of a bathtub vortex, Phys. Review Letters 91, 104501, 2003.
- [2] Andersen A. et al, The bathtub vortex in a rotating container, J. Fluid Mech. 556, pp121-141, 2006.
- [3] Foster, M.R., Asymptotic theory for a bathtub vortex in a rotating tank, J. Fluid Mech. 749, pp113-144, 2014.
- [4] Shapiro, A.H., Bath-tub vortex, Nature 196, pp1080-1081, 1962.
- [5] Trefethen, L.M. et al, The bath-tub vortex in the southern hemisphere, Nature 207, pp1084-1085, 1965.
- [6] Tyvand, P.A. and Haugen, K.B., An impulsive bathtub vortex, Phys. Fluids 17, 062105, 2005.
- [7] Yukimoto, S. et al, Structure of a bathtub vortex: importance of the bottom boundary layer, Theor. Comput. Fluid Dyn. 24, pp323-327, 2010.

## Diffusively-driven stratified flows in a sloping cube (A)

Background: In 1970, two independent studies (by Wunsch and Phillips) of the behaviour of a linear density-stratified fluid in a closed container showed that motion can be generated simply due to the container having a sloping boundary surface, and furthermore that the fluid flows uphill! This remarkable phenomenon is a result of the curvature of the lines of constant density near any sloping surface, in order that a zero normal-flux condition on the density to be satisfied along that boundary.

Since that time a number of studies have since considered the consequences of this type of 'diffusively-driven' flow, including in the deep ocean and with turbulent effects included. More recently, Peacock et al (2004) undertook an experimental study of the phenomenon in a closed container and Page & Johnson (2008, 2009) and Page (2011) extended the work to consider the broader-scale mass recirculation that is generated.

Objectives: The project will review and compare previous analytical, experimental and computational work on this problem for various geometries. The linear analytical approach introduced in Page & Johnson (2008) and Page (2011) will be used to predict the form of the steady flow and compare that with computational results from a numerical model of the full governing equations.

Expectations:

- review previous work on steady diffusively-driven flows in relation to the geometries studied and the key non-dimensional parameters;

- use the same approach to determine an analytical solution for the ‘outer flow’ within a sloping cube, based on the linear theory in Page & Johnson (2008) and Page (2011), as well as its more recent extension by French (2017);
- develop a simple computational model based on a pseudo-spectral collocation approach (eg Fornberg, 1998) for the steady linear driven viscous flow in a sloping cubic container and analyse those results for various alignment angles and moderately small values of the relevant non-dimensional parameter  $R$ .

Assumed knowledge: MTH3011, MTH3051 and MTH3360

Reading:

[1] Fornberg, B., A practical guide to Pseudospectral Methods, Cambridge, 1998.

[2] French, A., Diffusion-driven flow in three dimensions, PhD thesis, Monash University 2017.

[3] Page, M.A. & Johnson, E.R., On steady linear diffusion-driven flow, *J. Fluid Mech.* 606, pp433-443, 2008.

[4] Page, M.A., Steady diffusion-driven flow in a tilted square container, *Quart. J. Mech Appl. Math.* 64, pp319-348, 2011.

[5] Phillips, O.M., On flows induced by diffusion in a stably stratified fluid, *Deep-Sea Research* 17, pp. 435-443, 1970.

[6] Wunsch, C., On oceanic boundary mixing, *Deep-Sea Research* 17, pp293-301, 1970.

## Unsteady viscous flow in a ‘sliced cylinder’ (A)

Background: The ‘sliced cylinder’ configuration was introduced by Stommel (1948) as a simple two-dimensional ‘inviscid’ model for ocean circulation in the presence of variations in background rotation (such as occurs in practice with latitude). An analytical model was posed, based on the so-called beta-plane approximation, and it has an exact solution which demonstrates an intense ‘western boundary current’ under some conditions. Subsequently, laboratory simulations and numerical calculations for the corresponding viscous flow were undertaken by Beardsley (1969) and Beardsley & Robbins (1975). Becker & Page (1990) reinterpreted those numerical results in the unsteady, low viscosity regime and those results were examined further by Kiss (2002), also using an unsteady model but concentrating on the instability of the ‘inviscid’ part of the flow. Part of the issue here was about what was meant by ‘boundary-layer separation’ of the viscous Stewartson  $E^{1/4}$  layer adjacent to the boundary.

Objectives: The project will review previous analytical, experimental and computational work on this problem in the simple depth-independent case. A pseudo-spectral numerical model (eg Fornberg, 1998) for the unsteady two-dimensional flow in the low viscosity case will be developed, and this will be used to re-examine the conclusions from both Becker & Page (1990) and Kiss (2002). The key difference here is that the previous studies used unsteady models for the flow starting from rest, whereas the new approach will calculate the steady flow directly and then use that as an initial condition to examine how the unsteady flow behaves subsequently. This will then be used in several cases where the steady solution might be unstable in practice.

Expectations:

- undertake a thorough review of existing primary literature sources on this problem;
- identify the factors that influence the fluid motion, the key assumptions made;
- use those approaches to derive the corresponding governing equations and assess the relative size of the relevant nondimensional parameters;
- develop a simple but accurate numerical model for determining the steady two-dimensional flow in a ‘sliced cylinder’;
- extend that model to allow it to determine the corresponding unsteady flow;
- undertake simple computational experiments for the unsteady behaviour across a range of parameters in which ‘boundary-layer separation’ appears to occur.

Assumed knowledge: MTH3011, MTH3051 and MTH3360

Reading:

[1] Beardsley, R.C. A laboratory model of the wind-drive ocean circulation, *J. Fluid Mech* 38, p255, 1969.

[2] Beardsley, R.C. & Robbins, K. The ‘sliced cylinder’ laboratory model of the wind-driven ocean circulation. Part 1. Steady forcing and topographic Rossby wave instability. *J Fluid Mech* 69, p27, 1975.

[3] Becker, A. & Page, M.A. Flow separation and unsteadiness in a rotating sliced cylinder. *Geophys. Astrophys. Fluid Dyn.* 55, p89, 1990.

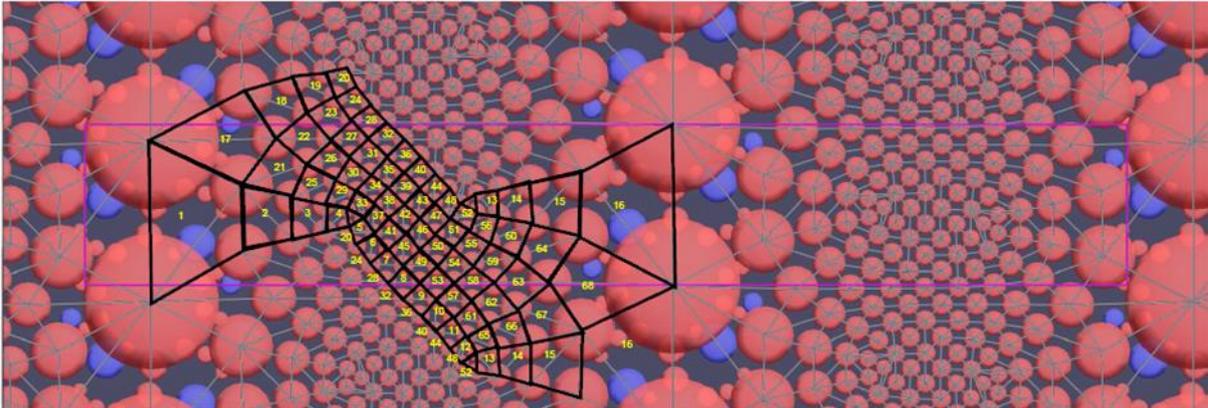
[4] Fornberg, B., A practical guide to Pseudospectral Methods, Cambridge, 1998.

[5] Kiss, A.E. Potential vorticity crises, adverse pressure gradients, and western boundary current separation. *J. Marine Res.* 60, p779, 2002.

[6] Stommel, H. The westward intensification of wind-driven ocean currents, *Trans. Am. Geophys. Union* 29, p202, 1948.

## Alternating shuffle braids (P)

Background: Many braids have an associated hyperbolic volume. I want to find braids with the largest possible volume per crossing number. A simpler sub-problem is to analyse a type of braid called an alternating shuffle braid, which seems to have very large relative volume, and to find bounds on its volume depending on its form. For classes of these braids, a simple pattern seems to be occurring in the geometry. An example is shown in the image below, which is a computer printout of the geometry of one alternating shuffle braid.



Project Outline: Which alternating shuffle braids have largest volume per crossing number? To answer the question, the first step is to analyse geometric structures of alternating shuffle braids, and to prove inductively that certain objects – tetrahedra and octahedra – appear in predicted patterns in the braids. The next step is to find estimates on the shapes of the tetrahedra and octahedra, and use them to bound volumes from above and below.

References:

[1] This project would generalise work in the paper: Champanerkar, Kofman, Purcell, “Volume bounds for weaving knots”, to appear in Alg. Geom. Topol., available at <http://front.math.ucdavis.edu/1506.04139>

More information on geometry and knots can be found in notes on my website:

<http://users.monash.edu/~jpurcell/hypknottheory.html>

## Knot invariants: Classical, Geometric, and/or Quantum (P)

Background: In the late 19th century, knots were studied by their diagrams and classified by things like their minimal number of crossings. By the middle of the 20th century, they were often studied by considering their complement: the space obtained by removing the knot from the 3-sphere. In the 1980s and 1990s, several new invariants were found. On the geometric side, it was discovered that knot complements often admit a unique hyperbolic metric, and so geometric quantities like volume become knot invariants. On a more algebraic side, new polynomial invariants such as the Jones polynomial were discovered. Even more recently, knot invariants have been discovered arising from quantum topology and homology theories. Many of these modern invariants are difficult to compute for particular knots. It is also often unknown how various invariants relate to each other.

Project outline: There are many possible projects depending on student’s interest and background. Possibilities include computing knot invariants for new classes of knots, investigating relationships between invariants, such as quantum and geometric.

Prerequisites: Ability to read and write proofs, interest in geometry and topology.

References:

[1] Adams, The Knot Book

[2] Purcell, Notes on hyperbolic knot theory, available here: <http://users.monash.edu.au/~jpurcell/papers/hyp-knot-theory.pdf>

**Note:** Other projects on the geometry, topology, and algebra of knots and links are also available under the supervision of Jessica Purcell.

## Variational methods in shape optimisation (A,P)

(Co supervised with Dr Yann Bernard)

Shape optimisation has various applications in theory as well as in industry. The minimisation of the drag of a vehicle, the maximisation of the effectiveness of a magnet with given weight in a wind turbine and the reconstruction of the most likely shape of an object by tomography are particular examples of shape optimisation problems.

From a mathematical perspective, a shape optimisation problem is an optimisation problem, where the optimisation variable is a subset of a Euclidean vector space. As the collection of these subsets has no linear structure, standard approaches to optimisation problems do not work in this setting.

The aim of this project is to work through the first chapters of the books *Introduction to Shape Optimisation* by Sokolowski and Zolesio and *Variational Methods in Shape Optimisation Problems* by Bucur and Buttazzo to obtain a thorough understanding of the problem as such. The second step will be a numerical treatment of a selected shape optimisation problem.

The prerequisites for this project are a solid knowledge in real analysis and linear algebra. Familiarity with functional analysis, partial differential equations, nonlinear optimisation and computational mathematics is beneficial, but not required.

## Exploring variants of the subdivision algorithm (A)

The subdivision algorithm by Dellnitz and Hohmann is a well-established numerical method for the computation of invariant sets of discrete-time dynamical systems. It covers the relevant region in phase space by a collection of boxes, which it successively refines and reduces until a good approximation of the desired object is obtained.

In the case of continuous-time dynamical systems, it has been common practice to simulate the time-1 flow, thus generating a map to which the subdivision algorithm can be applied. It has recently been noticed that this treatment of the continuous-time case is not only inefficient, but it also does not take into account several features of a flow which can be exploited to improve the algorithm substantially. In particular, it is possible to couple the length and the accuracy of the time integration with the accuracy of the spatial discretisation without losing convergence of the overall scheme.

The aim of the project is to understand the theoretical concepts behind the subdivision algorithm and to explore the impact of various time integration strategies in numerical experiments. A solid background in ordinary differential equations and programming skills are required. Basic knowledge on numerical methods for ordinary differential equations is recommended.

## Stabilisation of a bipedal robot (A)

Bipedal robots are complex machines that carry out tasks while moving in space. In contrast to robots moving on a wheeled chassis, their stabilisation is relatively difficult and computationally expensive. The aim of this project is to learn how to shift computational cost from the online to the offline phase by computing viability domains, which are safe regions in parameter space.

The project will start with an exploration of viability techniques for the inverted pendulum, which is a classical benchmark in numerical stabilisation. When the analytical and numerical techniques are understood, they will be applied to an inverted pendulum with multiple joints, which is -- in a sense -- similar to a bipedal robot. Should the results be satisfactory, the algorithms may later be transferred to a bipedal robot.

Depending on opportunity, the project will be carried out together with a fourth-year engineering student. In the early stages of the project, this partner could give feedback on the performance of different viability techniques applied to a physical inverted pendulum. Later, the partner would build a physical inverted pendulum with multiple joints, on which the software to be developed could be tested.

Prerequisites for this project are a solid knowledge in analysis, calculus and linear algebra, computational mathematics and ordinary differential equations, as well as basic, but solid programming skills.

## The fluid dynamics of blood pattern analysis (A)

Background: In the Sherlock Holmes story "A Study in Scarlet", Holmes is asked to help Scotland Yard in a murder case: a man has been found dead in an abandoned house. Blood is in the room, but there is no mark on the body. From a careful analysis of the blood and other apparently innocuous observations, Holmes gives a detailed and accurate description of the murderer. Blood pattern analysis is now a common and fundamental part of forensic analysis at a crime scene, allowing reconstruction of events such as the type of injury, movements of the victim, relative angles of perpetrator and victim and more. However, in 2009 the National Academy of Sciences in the US released a damning report on the scientific basis for many forensic methods. With regards to blood pattern analysis, the report states it is "more subjective than scientific", the "uncertainties are enormous" and the "emphasis on experience over scientific foundations seems misguided, given the importance of rigorous and objective hypothesis testing and the complex nature of fluid dynamics".

Project outline: This project would start with a review of the relevant literature on blood pattern analysis and the relevant fluid dynamics (Attinger et al below being a good starting point). From there, a range of projects are possible depending on your interests. These can include theory, experiments and/or simulations. An example project would be the difference in blood droplet splash patterns depending on whether the impact surface is solid or cloth.

Prerequisites: MTH3360 or equivalent

References:

- [1] "Strengthening Forensic Science in the United States: A Path Forward", National Academy of Sciences, 2009 ([http://www.nap.edu/download.php?record\\_id=12589#](http://www.nap.edu/download.php?record_id=12589#))
- [2] D. Attinger, C. Moore, A. Donaldson, A. Jafari and H. A. Stone "Fluid dynamics topics in bloodstain pattern analysis: comparative review and research opportunities", Forensic Science International, 231, pp 375-396, 2013 (<http://www.sciencedirect.com/science/article/pii/S0379073813002417>)

## Rafts of floating pebbles: surface tension versus gravity (A)

(co-supervised with Dr Julie Clutterbuck)

Background: On very calm days, rafts of rather flat pebbles can sometimes be observed floating on the sea. Although they are denser than water, they are kept afloat by surface tension. This phenomenon is pervasive elsewhere, such as fire ants collecting their queen and eggs and forming a raft during floods. More practically, surface-tension-driven raft formation is being explored as a means of assembling microscopic systems.

Project outline: This project investigates the largest possible size that a pebble raft can take. It will involve calculating the total energy of the system and minimizing that energy to find a system of ordinary differential equations. These will be solved using MATLAB (or otherwise). The theoretical results will be compared with simple experiments.

Prerequisites: MTH3011 and MTH3140

References:

- [1] D. Vella, P.D. Metcalfe and R.J. Whittaker "Equilibrium conditions for the floating of multiple interfacial objects", Journal of Fluid Mechanics, 549 pp. 215-224 (<http://dx.doi.org/10.1017/S0022112005008013>)
- [2] Fireants: <http://www.youtube.com/watch?v=L2ZysgGAABw>
- [3] G. Whitesides, B. Grzybowski "Self-assembly at all scales", Science, 295 no. 5564 pp. 2418-2421, s00s (<http://www.sciencemag.org/content/295/5564/2418.full>)

## Laminar-turbulent transition on an aerofoil (A)

Background: Steady 2D flows that develop on a wedge are known as Falkner-Skan boundary layers and are a prototypical configuration for the study of laminar-turbulent transition on unswept aerofoils. The family of flows are susceptible to small linear instabilities known as Tollmien-Schlichting waves. These waves are slowly amplified as they develop downstream, eventually bringing about nonlinear effects and transition to turbulence [1, 2]. The ability to predict the onset of these Tollmien-Schlichting waves is critical for determining flight performance capabilities. Thus, robust numerical methods are required to accurately compute unstable behaviour and improve the design of future aircraft wings.

Project outline: The student will derive and solve the Falkner-Skan equations for a range of wedge angles. The student will then develop a numerical scheme [3] and undertake a linear stability study of these flows. Conditions necessary for the onset of unstable Tollmien-Schlichting waves will be determined.

Prerequisites: MTH3360 and Matlab experience.

### References:

- [1] Schmid, P.J. & Henningson, D.S., "Stability and Transition in Shear Flows", Springer-Verlag, New York, 2001.
- [2] Drazin, P.G. & Reid, W.H., "Hydrodynamic Stability", Cambridge University Press, 2004.
- [3] Thomas, C., "Numerical simulations of disturbance development in rotating boundary layers", PhD Thesis, Cardiff, 2007.

## Statistical inference of genetic regulatory networks (S)

Background: Investigating the dynamics of genetic regulatory networks through high throughput experimental data, such as microarray gene expression profiles, is a very important research topic in biological sciences. Although a variety of inference methods have been designed over the last ten years, it is still a challenge problem in bioinformatics and computational biology. One of the major hindrances in building detailed mathematical models for genetic regulation is the large number of unknown model parameters.

Project outline: This project commences with the analysis of gene expression data such as microarray data and RNA-seq data. Then you will implement different modelling approaches to reconstruct the regulatory network. The p53 gene network will be used as the test problem. There are two possible projects under this topic:

1. You may study the top-down approach uses probabilistic graphical models to predict the network structure of genetic regulatory networks. You may consider different graphic models such as Gaussian graphic model or Bayesian graphic model.
2. You may study the bottom-up approach using differential equation models to investigate the detailed genetic regulations based on either a fully connected regulatory network or a gene network obtained by the top-down approach.

### Reference

- [1] Wang J, Wu Q, Hu XT, Tian T. An integrated approach to infer dynamic protein-gene interactions - A case study of the human P53 protein. *Methods*. 2016 Nov 1;110:3-13.
- [2] Wang J, Tian T. Quantitative model for inferring dynamic regulation of the tumour suppressor gene p53. *BMC Bioinformatics*. 2010 Jan 19;11:36.

## Stochastic simulation of biochemical reaction systems (S)

Background: There is a growing body of evidence which suggests the dynamics of biological systems in the cell, especially genetic regulation, is stochastic. One of the major reasons is the small molecular numbers of proteins in the cell such as transcriptional factors and message RNA. Biochemical reaction systems are typically studied using the stochastic simulation algorithm (SSA). Recent progress in computational biology has proposed mathematical models for large-scale complex biological systems. There is a strong need to develop efficient and effective numerical methods for simulating the dynamics of stochastic biological systems.

Project outline: This project commences with the implementation of the SSA for simulating genetic regulatory networks. Then you will implement more efficient methods such as the tau-leap methods and multi-scale simulation methods. There are two possible projects under this topic:

1. You may study the dynamic property of a specific biological network in genetic regulation or cell signalling transduction by using stochastic simulation methods. An interesting question of this project is the function of noise in maintaining bistability property of gene networks.
2. You may study effective simulation techniques, including the implementation of stochastic simulation on high performance computers, to simulating biochemical reaction systems.

### References

- [1] Gillespie D.T., "Stochastic simulation of chemical kinetics", *Annual Review of Physical Chemistry*, 58, 35-55, 2007.
- [2] Tian, T. and Burrage, K., "Binomial leap methods for simulating stochastic chemical kinetics", *Journal of Chemical Physics* 121, 10356-10364, 2004.
- [3] Burrage, K., Tian, T. and Burrage, P.M., "A multi-scaled approach for simulating chemical reaction systems", *Progress in Biophysics and Molecular Biology*, 85, 217-234, 2004.

## Permutation polynomials (P)

Let  $F$  be a finite field of order  $q$ . Any permutation of  $F$  can be achieved by evaluating a polynomial of degree at most  $q-2$ . However, not all polynomials produce permutations. This project studies tools for diagnosing whether a polynomial produces a permutation. We also look at the cyclotomic structure of finite fields and how this can be used to define particular nice permutations/polynomials, that have lots of marvelous properties and applications.

If done as a major project the original work would involve a computer aided exploration of orthogonality between cyclotomic permutations (two permutations are said to be orthogonal if their difference is also a permutation). In particular, we would look for large sets of pairwise orthogonal permutations and try to identify patterns that can be written down and proved in generality.

Prerequisite: MTH3150

References:

[1] Lidl and Niederreiter, Finite fields

[2] Encyclopedia of Mathematics and its Applications 20. Cambridge University Press, 1997.

## A permutation game (P)

Let  $n$  be a positive integer and let  $S$  denote the set of all permutations of the numbers  $1, 2, 3, \dots, n$ . So if  $n=3$  then  $S=\{123,132,213,231,312,321\}$ . Consider the following game played with these permutations:

The game has three stages, and each person sees the other person's choices:

- 1) I choose a subset  $T$  of  $S$ .
- 2) You choose a permutation  $p$  in  $S$ .
- 3) I choose a permutation  $q$  in  $T$ .

The score is then calculated as the number of positions in which  $p$  and  $q$  agree. For example, if  $p=132$  and  $q=231$  then the score is 1 since  $p$  and  $q$  agree in the second position.

My aim is to score as highly as possible and your aim is to keep the score as low as possible.

Question: Suppose I want to guarantee a score of at least  $s$ . How small can  $T$  be?

This question has been answered only in very simple cases, such as  $s=1$  or  $s=n-1$ . Even solving the  $s=2$  case might answer some important problems in discrete mathematics. However, there have been several interesting papers written on this problem and its connections to other areas of mathematics. These papers would be the subject of the reading project.

## Latin squares (P)

Latin squares are a two dimensional analogue of permutations. A Latin square of order  $n$  is an  $n$  by  $n$  matrix in which each of  $n$  symbols occurs once in each row and in each column. These days you'll find Latin squares on the puzzle page of every major newspaper as well as in the schedule for sports tournaments and statistical experiments. In pure mathematics, Latin squares are fundamental objects. Every finite group is defined by its Cayley table ("multiplication" table), which is a Latin square. Similarly, in finite geometry projective planes are defined by certain sets of Latin squares.

**Project Outline:** There are a range of possible projects goals available, exploring the structure and uses of Latin squares. All would be combinatorial in nature but depending on your interests they could also have an algebraic, algorithmic, probabilistic, geometric or enumerative flavour. Drop in to discuss the options if you are interested.

References:

[1] Laywine, C.F. and Mullen, G.L. "Discrete mathematics using Latin squares", Wiley, New York, 1998.

[2] Recorded Lectures (especially lectures 1,3,5,6,7) at: <http://qtss.amsi.org.au/SummerSchool2004gra.html> also the latter part of the mathematical/historical/comedy piece: <https://www.youtube.com/watch?v=gONv139Jd2Y>

## Graph factorisations (P)

Background: Suppose  $n$  points are placed in general position (no 4 are co-planar). Between each pair of points, colour the line joining those points subject to the conditions:

(i) Only  $n-1$  colours are available.

(ii) No two lines meeting at a point may have the same colour.

(iii) For every choice of two points and two colours it must be possible to travel between the chosen points along lines of the chosen colours.

In graph theory terminology you have found a perfect 1-factorisation of the complete graph  $K_n$ .

For a project in this area you would study what is known (and what is not known) about perfect factorisations. This could include some group theory if you want to study their symmetries, or some computational work, looking for perfect factorisations (but it doesn't have to involve either).

References:

[1] Wallis, W.D., "One-factorizations", Math. Appl. 390, Kluwer Academic, Dordrecht, 1997.

### **Topics in structural graph theory (P)**

Abstract: Graph theory is the mathematics of networks. Structural graph theory looks at topics like graph colouring, planarity, graphs on surfaces, graph minors, and tree width. In this project, several papers on a specific area of research will be reviewed with the goal of improving on the existing results.

Skills required: A love of mathematics, and the ability to read, understand and write mathematical proofs.

Units Required: MTH3170 Network Mathematics and the honours Combinatorics unit

## Random graphs (P)

Background: A graph or network is a set of points called 'vertices' and links between the nodes called 'edges'. Random graphs involve some random choices in determining the edges. Random graph theory was first used last century to show the existence of graphs with special hard-to-construct properties. Since then, it has been used to answer many questions arising in computer science, as well as generating questions of intrinsic interest. These questions usually ask for the properties of a large random graph. Sometimes the problem is to make a random graph in some weird way so that it is likely to have some desirable property, such as with graphs called random "lifts".

Project outline: There are many possible projects. Here is one. The game of "cops and robbers" is played on a graph. The cops are moved by one player and the robbers by another. First the cops are placed on the graph, then the robber. Then each cop can move to an adjacent vertex, then the robber can move similarly, and so on. For a given graph, how many cops are required to ensure being able to catch the robber eventually? An unsolved problem (Meyniel's conjecture) is to show that some constant times the square root of the number of vertices is always sufficient. The best known bounds are far from this. We can ask whether random graphs satisfy the conjecture.

Reference

[1] Janson, Luczak and Rucinski, "Random Graphs".

## Modelling the World Wide Web (P)

A modern topic at the interface of mathematics with computer science and physics is task of making simple theoretical models of "naturally" occurring network structures. Even with simple-sounding rules for their evolution, randomly evolving networks can have some surprising properties. One of the well known examples of these regards the degrees of the nodes, i.e. the numbers of links they have to other nodes. These often follow a somewhat mysterious "power law". Another property was popularised under "six degrees of separation": there is usually a "short" path between any two nodes. The aim of the project is to look at these questions from the pure mathematical side, investigating the rigorous proofs of such properties. Such questions are solved for some kinds of networks but unsolved for many others.

Skills required: Some familiarity with probability is highly desirable.

## Counting using complex numbers (P)

Background: If you want to count something, like the ways to insert balls into boxes under certain restrictions, or the ways to walk from A to B on some kind of grid in a given number of steps, then power series can help. The number of things is a coefficient in the power series.

Sometimes the coefficient is horribly complicated and a much simpler approximate answer exists. Important methods of obtaining such answers use complex analysis, including complex integration.

The project: After learning about the methods of counting, there are a number of problems that can be addressed. Suppose you are allowed to walk to the right along the integer line taking steps of a restricted set of lengths. In how many ways can you reach distance  $n$ ? What if you are restricted so that you must "touch base" on each multiple of  $k$  along the way? The same techniques can answer not just counting questions, but questions about random walks, where each step length has a certain probability.

Prerequisite: Knowledge of complex analysis and power series is required.

References

[1] H. Wilf, "Generating functionology"

[2] P Flajolet and R Sedgewick, "Analytic Combinatorics"

## How fast do rumours spread? (P)

Background: In the beginning, somebody starts a rumour by telling a friend. Each day, everybody who knows the rumour calls one of their friends at random and tells them the rumour. How long do we expect it to take before everybody knows the rumour? This simple question has implications for distributed computing.

Project outline: The answer to the rumour question depends on the structure of the network of friends. We can ask which network structures of  $n$  friends are likely to take longest for the rumour to spread. We can ask if the rules of spreading are changed, how does it affect the spread time. In considering these questions you will learn about some simple probability processes, some graph theory, and possibly something about random graphs.

Skills required: some familiarity with probability is highly desirable.

