THE UNIVERSITY of ADELAIDE

Summer Research Scholarships

School of Mathematical Sciences

Project Titles

Spreading wavefronts

A range of quite different phenomena can sometimes be characterised as a wavefront spreading into new regions. Examples include tsunamis, the population density of an invasive species, the cancer cell density in a spreading solid tumour, and the temperature profile in a bushfire. This project will focus on numerical solutions of partial differential equations modelling one or more of these phenomena in order to determine how fast the front is spreading. This project has applicability in for example understanding the factors leading to a rapid spread of cancer, or in evaluating how some intended treatment may mitigate its spread. *Prerequisites: a second-year differential equations course, and strong programming capability in Matlab.*

Characterising chaos

This project will study the concept of chaos from a mathematical viewpoint. Qualities which characterise chaos (e.g., sensitive dependence on initial conditions, presence of periodic orbits of all periods, uncountably many aperiodic orbits, and dense orbits) will be studied. Methods for analytically proving that a system is chaotic (presence of a "horseshoe," intersection of stable and unstable manifolds, Melnikov's method) will be applied to different systems arising in applications. *Prerequisites: a second-year differential equations course and an interest in theoretical methods of differential or difference equations.*

Unsteady flow barriers

In unsteady (time-varying) flow fields, there are usually important invisible flow barriers which move with time. Examples include the boundary of an area ("the forbidden zone") near the coast of Florida into which the Deepwater Horizon oilspill did not leach, and the edge of the Antarctic Circumpolar Vortex ("the ozone hole"). This project will focus on understanding and using recently developing methods for identifying such flow barriers, and (depending on student background) will choose from George Haller's methods of curves of maximal attraction, Gary Froyland's transfer operator methods and/or Jean-Luc Thiffeault's topological complexity of curves method. *Prerequisites: a second-year differential equations and fluid dynamics course, plus either a strong theoretical mathematics or programming background.*

Numerical computation of stable and unstable manifolds

The "flow barriers" described in the previous project can be recast theoretically as "stable and unstable manifolds." In two-dimensional flows, for example, these would be time-varying curves which exhibit complicated intersections patterns with each other, and forms the template which governs how fluids mix. Numerically determining these for time-varying (unsteady) velocity fields remains a challenging problem. In this project, the student will build on a currently existing numerical algorithm to seek highly refined stable and unstable manifold curves. *Prerequisites: strong programming capability in Matlab.*

I am also open to topics in other areas, to be agreed upon after discussion with me.

Supervisor: Dr Sanjeeva Balasuriya

I am happy to discuss possible topics for a research project in areas such as differential geometry, topology and complex analysis.

Supervisor: Dr David Baraglia

I am happy to supervise projects in the areas of finite geometry and combinatorics. Interested students can email me to arrange a meeting and we can discuss possible project ideas.

Supervisor: Dr Susan Barwick

Stochastic modelling using structured Markov chains

In this project we will investigate the mathematical properties of some very recent stochastic models. These models have been developed from the basic principles used in a field known as "Matrix-analytic Methods" (or MAM) where simple exponentially distributed lifetimes are replaced by lifetimes from more complex distributions. When done carefully, the analysis of the whole model becomes matrix-based, rather than scalar-based, hence the name. Of course, this brings all sorts of challenges (for example, the square root operation no longer makes any sense) and requires a much closer connection to the physical model itself. This, and an associated emphasis on computational algorithms, are the main features of this area of stochastic modelling.

Supervisor: Professor Nigel Bean

Quantifying and modelling yeast colony spatial patterns

Yeasts colonies can forage for food by either the process of filamentous growth, or the formation of a biofilm. Both are highly non-uniform spatial-temporal processes, often producing complex spatial patterns. The overall goal of this project is to develop models that predict the time evolution of colony morphology. However, an important part of this work is the spatial quantification of yeast growth experiments, which can be used to validate modeling predictions. Therefore, one of our aims is to develop user-friendly open source software that can process experimental images and provide metrics on the spatial patterning of colony morphology. The second aim is the modeling itself, and both continuum and discrete approaches could potentially be explored during the course of the project. The data for the statistical analysis and model validation will be obtained from laboratory experiments.

Supervisor: Associate Professor Ben Binder

Evolution of life cycles in multicellular collectives

Simple multicellular collectives, such as chains of bacteria, are of interest because they are the starting point for all further multicellular evolution. The emergence of life cycles and basic developmental processes are key steps in multicellular collectives becoming fully-fledged organisms. This project will involve using stochastic techniques to build models of these biological systems. These will then be studied using a combination of analytic and simulation methods.

Inference methods for epidemic models

A crucial part of epidemic modelling is to characterise a disease in the early stages of an outbreak so as to inform public health policy and implement measures to slow its spread.
This project will involve learning methods for computational Bayesian analysis and applying them to household models of influenza.

Supervisor: Dr Andrew Black

Nanoscaled oscillating systems

Nonoscaled structures such as carbon nanotubes and fullerenes undergo interactions described by van der Waals forces. At very small scales these interactions can lead to extreme accelerations, velocities and, in the case of oscillating systems, frequencies. By modelling the structures as surfaces with uniform atomic densities and the van der Waals interactions using a 6-12 Lennard-Jones potential, we can make predictions regarding these systems including deriving a formula for the frequency which is in good agreement with molecular dynamics simulations. In this project the student will look at models to calculate the force and predict the behaviour of various oscillating systems.

Geometries and geometric issues of nanostructures

It is clear from the various structures seen at the nanoscale that the complex interactions of these structures often lead to symmetric conformations. So in satisfying a minimum energy constraint the system often adopts a symmetric structure that shares the energetic costs of bending and stretching covalent bonds equally to all components in the structure. By assuming a symmetric conformation up front, it is possible to reduce fundamentally complex problems of molecular structure to problems with are more mathematically tractable and thereby derive results which can be confirmed by experiment and simulation and can also be used to predict ideal systems and novel structures in certain extreme cases. In this project the student will study models for nanostructures such as nanotubes, cones and spheres (buckyballs) with the aim to provide more precise predictions of structural parameters like length and radius.

Supervisor: Dr Barry Cox

Index theory

In index theory, people study relations between geometry, topology and analysis though indices of differential equations. Such an index is the difference between the dimensions of the solution spaces of two related differential equations. An index theorem states that such an analytically defined number equals a geometrically defined number. And both numbers turn out to be topological in nature, which means that they don't change if we continuously deform a differential equation or a geometric space. The most famous index theorem is the one proved by Atiyah and Singer in 1963, which generalised many earlier results in geometry.

Index theorems lead to deep connections between for example the curvature of a space and certain differential equations on it. In this project, we start by exploring the kind of equations that have well-defined indices. Then we investigate the Toeplitz index theorem, which illustrates many aspects of index theory.

Prerequisites: Topology and analysis

Noncommutative topology

All properties of nice enough topological spaces, specifically locally compact Hausdorff spaces, are encoded in the continuous functions on them. These continuous functions form a vector space, and also a commutative ring, via pointwise multiplication. These structures together make this function space an algebra, and it actually has the further structure of a C*-algebra. So one can study a locally compact Hausdorff space via its algebra of continuous functions, which is a viewpoint that sheds new light on many questions and constructions.

But more generally, one can also study noncommutative C*-algebras, which are interpreted as algebras of functions on “noncommutative spaces”. This can be used to study difficult spaces, such as non-Hausdorff ones. In this project, we will look at what C*-algebras are, and how tools from topology can be generalised to this framework.

Prerequisites: Groups and Rings, Topology and Analysis.

The geometry of classical mechanics

The mathematical language of classical mechanics is symplectic geometry or Poisson geometry. These areas of geometry are about spaces with structures that allows one to state Newton's laws on them. These spaces should be thought of as the sets of all positions and momenta a mechanical system can have.

E.g. for a double pendulum (a pendulum hanging from another pendulum), the space is the 2-dimensional torus plus all of its tangent planes. The torus, i.e. the Cartesian product of two circles, parametrises the position angles of the two pendulums, while the tangent planes parametrise the momenta, or velocities, of the two pendulums.

In this project, we will see how to formulate the laws of classical mechanics in terms of Poisson or symplectic geometry. We will explore some aspects of this point of view and/or apply the theory to a concrete example.

Groups and representations

Representations of a group are ways in which this group encodes the symmetry of a physical, chemical or mathematical object. We can look at various aspects, examples and applications of representation theory, especially for Lie groups. These are essentially groups of matrices. Applications to classical mechanics or particle physics are among the many possible topics.

I am also happy to discuss other projects in differential geometry, Lie group theory or analysis on manifolds. Any project can be adapted to the student's knowledge.

Supervisor: Dr Peter Hochs

The Classical Groups

The classical matrix groups are defined as invariance groups of certain multilinear maps on real, complex and quaternionic vector spaces. The aim is to study them as curved spaces within the vector space of n-by-n matrices and to establish some of the interesting relations between them that exists for small n. Further exploration can be related to topological properties of the classical groups or to the quotient spaces arising from them.

Quaternions and Octonions

In a similar way how the complex numbers are constructed from the reals, the quaternions are constructed from the complex numbers and the octonions from the quaternions. Thus, both can be considered as generalisations of complex numbers to higher dimensions. Many interesting algebraic and geometric phenomena are related to the quaternions and octonions. To explore these features and relations is the aim of the project.

Other possible projects

Apart from these two topics I am happy to discuss any topic that is related to differential geometry.

Supervisor: Dr Thomas Leistner

#selfies and emotional expressiveness

Bizarrely, there is evidence a facial asymmetry in the way human beings express emotions in photographs: people who face the camera with their right side leading are considered to be more emotionally expressive than those who lead with their left side. This effect has recently been studied in photographs of various groups of people, including academics and doctors. In this project we will collect and analyse selfies from Instagram to see how this facial asymmetry effect relates to different personality types on social media. After collecting a dataset and categorising individuals into left-facing and right-facing groups we will then test for differences in language using a combination of statistical and sentiment analysis techniques.

This project will involve some data mining and analysis using tools like Python and/or MATLAB – familiarity with one or both will be very desirable (and you'll learn more useful tools such as how to access data using APIs over the course of the project!).

Do the rich get richer on reddit?

The "Matthew Effect" is the widely-observed phenomenon whereby the rich get richer, or popular get more popular. Very famous models such as "preferential attachment" in network science have been used to explain diverse phenomena such as word distributions in language, scientific citation networks and more. In this project we will investigate whether the Matthew Effect exists in online social media, particularly in submissions to the popular website reddit. We'll collect time-resolved data on submissions to various subreddits using the reddit API, and then analyse the statistics of these data to try and detect the Matthew Effect. Along the way we'll encounter Simon's model, preferential attachment, and other interesting topics in complex systems science.

This project will involve some data mining and analysis using tools like Python and/or MATLAB – familiarity with one or both will be very desirable (and you'll learn much more as the project goes on!).

Studying humans 'in the wild' via social networks and Big Data

With the explosion in recent times of data from large-scale social networks such as Facebook and Twitter comes unprecedented opportunities to bring quantitative and computational methods to bear on problems in social, cultural and political science. This emerging field of computational social science blends mathematical and statistical techniques with computer science and very large data sets to study and predict the behaviours of groups of people based on their online activities — by observing them 'in the wild'.

We will analyse unique datasets comprising millions of tweets to look for trends in human dynamics. There are many potential topics here, possible case studies include:

1. Sentiment analysis of the #qanda audience for the purpose of real-time political polling;
2. Extracting daily mobility patterns from geolocated tweets to infer human dynamical patterns – these have particular relevance in fields like disease modeling;
3. Can you predict the #hottest100 using social media data? In particular, how close can you get using Triple J's playlist data coupled with mentions on social media? (This will probably require some scrounging for data…)

While rather computational in nature (we will be making use of programming languages like Python or MATLAB to make sense of these data sets; familiarity with one or both of these would be desirable), this project will provide the opportunity to engage with large, real-world data sets, and to do original research in an exciting new field.

Understanding and visualising demographic differences in sentiment on social media

This project will introduce you to some data science techniques in the fields of natural language processing, sentiment analysis, and social media analytics. The aim is to explore some new datasets comprised of dictionaries for quantifying "happiness" in written text for different languages, see http://www.pnas.org/content/112/8/2389. We will do a deep dive into these datasets to understand how sentiment relates to demographics, develop tools to visualise these differences, and use these new dictionaries within machine learning models for predicting sentiment.

While rather computational in nature (we will be making use of programming languages like Python or MATLAB to make sense of these data sets; familiarity with one or both of these would be desirable), this project will provide the opportunity to engage with large, real-world data sets, and to do original research in an exciting new field — this will be the first in-depth study of these datasets! This project can be adapted to take as many students as wish to sign up for it.

Supervisor: Dr Lewis Mitchell

Differential geometry
Mathematical physics

I am happy to discuss possible topics in the areas of differential geometry and mathematical physics. Interested students should email me and arrange a meeting.

Supervisor: Professor Michael Murray

Explode or Extinct?

Branching processes are mathematical models used to describe and analyse how populations evolve over time, with applications in many areas such as biology, epidemiology, computer science and image processing. Students can study the effects of initial starting points and growth rates on the eventual size of the population, via algorithms and/or probabilistic analysis.

What does the Apollo spacecraft and Wall Street have in common?

Diffusion processes played an important role in estimating the trajectories of the Apollo spacecraft on its way to the Moon and back, as well as in building the myriad of intricate models that is today's financial world. Students can study the effects on key properties of diffusion processes when we impose boundary constraints on these models.

How likely is that?

Natural disasters, financial crises, large-scale accidents and system breakdowns are examples of phenomena with extreme consequences that occur with non-negligible frequencies. Heavy-tailed models are able to capture adequately the behaviour of this type of phenomena but are often intractable. Students can study a class of models associated with infinite-phase-type distributions that can replace heavy-tailed models, from numerical and/or theoretical perspectives.

Supervisor: Dr Giang Nguyen

Help develop a toolbox for multiscale simulation and analysis

Often a researcher/practitioner has a detailed and trustworthy computational simulation of some problem of interest. The simulation is written in terms of micro-field variable values. Typically a desired simulation over large space-times would take far, far too long. We are developing and proving techniques to enable such simulation using projective integration and patch dynamics. The project over summer is to help create a Matlab toolbox for users around the world to automatically use the techniques on problems of interest.

Establishing critically useful theory for modelling.

Recently we are understanding more and more about the fundamental relationships between mathematical models at different levels of detail. It turns out that the so-called Centre Manifold Theory provides the rigorous support needed for such understanding. However, the extant theory only deals with the mathematical ideal case of exact results for precise systems on infinite times in an unknown domain. In practice we need theory valid for uncertainly known systems over finite times in a known finite domain. The project is to continue work developing theory to generate such useful practical theorems to underpin mathematical modelling.

Supervisor: Professor Tony Roberts

Establishing evidence for a new policy for pandemic influenza response

Our recent research has suggested a new approach to the use of antivirals (and other interventions) in the event of an influenza pandemic. Further modelling work is required to establish its validity as a useful policy in practice. This project will assist in determining this evidence base. It will involve learning about stochastic models of infectious disease dynamics, and simulation algorithms; some programming (for example in MATLAB) will be required.

Valuing data in inference methods, and the optimal collection of data

In many studies where we wish to learn about a system, we have choice over the information we collect subject to some resource constraints. How should one choose the data to collect? This project will consider ways to define the "value" of data, and look at the effectiveness of some simple approximations for making this choice. A particular motivation will be the choice of different sized populations (e.g., small households, large households, or schools) when estimating disease parameters.

Supervisor: A/Professor Josh Ross

Statistical machine learning

In this Summer Project, you will learn about statistical machine learning using R. The starting point will be analysing data using regression and classification trees which will lead you onto random forests and support vector machines. You will also learn how to choose models using k-fold cross-validation and analyse high-dimensional datasets on cancer and prediction of molecular activity.

Supervisors: Professor Patty Solomon

Algebraic topology or category theory

I am happy to supervise projects in algebraic topology or category theory. If you are interested, please email me to arrange a meeting to discuss possible topics.

Supervisor: Dr Danny Stevenson

Geometry and topology

I am happy to supervise projects in differential geometry, topology and related areas. If you are interested, please email me to arrange a meeting and we can discuss possible topics.

Supervisor: Dr Raymond Vozzo

Geometry and symmetry

I am happy to supervise summer research topics related to topology and geometry, geometry of noncommutative spaces, Fourier and harmonic analysis, groups and number theory. Interested students are encouraged to email or talk to me to figure out a detailed plan. I have successfully supervised a summer project 2014-15 supported by AMSI Vacation Research Scholarship.

Supervisor: Dr Hang Wang