UNIVERSITY OF CAMBRIDGE
School of Technology

UNIVERSITY OF CAMBRIDGE
School of the Physical Sciences

STEM Research Internship Scheme

Summer 2024

Project List

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Institute of Astronomy

(1) Populations of helium stars in the Local Group

Project Supervisor: Dr Avishai Gilkis

Host Department/Institute: Intitute of Astronomy

Project Outline:
Stellar evolution theory informs us that evolved stars which lose their hydrogen envelopes become hot helium stars. These correspond observationally to low-mass hot subdwarfs, or luminous massive Wolf-Rayet stars with powerful stellar wind outflows.

A long-standing issue in the study of stars was that while theory predicted the existence of many stars between subdwarfs and Wolf-Rayet stars, none were observed. Recently, Drout et al. (2023) discovered populations of intermediate-mass helium stars in two Milky Way satellite galaxies – the Small Magellanic Cloud and the Large Magellanic Cloud. Finding these intermediate-mass helium stars qualitatively resolves the aforementioned mismatch between theory and observation, and now is the time to quantitatively investigate how well stellar theory fits with the new discovery.

The aim of the proposed research project is to construct synthetic populations of stars in different Local Group environments, based on detailed stellar evolution simulations of binary stars. The student will develop a code that takes as input a star-formation history and initial distributions of stellar properties and then samples the simulations to generate synthetic populations, for various plausible assumptions. The properties of the intermediate-mass helium stars in the simulated populations will be assessed and compared to the recent observations. These properties include distributions of mass, temperature, luminosity and composition, as well as orbital configurations and the nature of a companion star in a binary system, which can be a normal star, white dwarf, neutron star or black hole. Such quantitative comparisons are a crucial test of stellar theory, and the understanding of the newly-discovered intermediate-mass helium stars is opportune, as they are potential sources of cosmic ionising radiation and supernova progenitors.

Five key words for this project: helium star evolution, stellar populations

Chemical Engineering and Biotechnology

(2) CO_2 capture with nanomaterials- overcoming the thermodynamics constraints to enable inexpensive CO_2 capture directly from air

Project Supervisor: Dr Ewa Marek

Host Department/Institute: Chemical Engineering and Biotechnology

Project Outline:
CO_2 removal from air is essential to reach Net-Zero by 2050. The current technologies are energy-intensive and cost ~£500/tCO_2. Understandably, capturing CO_2 from air is difficult because of its low concentration, ~420 ppm, which translates to a small driving force for CO_2 sorption. Energy Reactions and Carriers Group has developed a new type of sorbents, that can help overcome this thermodynamic limitation. Our new sorbents are based on inexpensive CaO-nanoparticles, that reversibly bind CO_2 into $CaCO_3$ already at 100ºC, with regeneration at 150ºC – this is a tremendous improvement over similar materials working at 500 and 700ºC for both steps, respectively.

In this project, you will tune our novel sorbents for CO_2 capture to improve their sorption capacities. To accomplish this, a high surface area support material, doped with an alkaline metal, will be impregnated with an alkali-based ionic liquid, while the synthesis will be controlled to affect the size of CaO particles. Thermal pre-treatment will be varied to tune physical characteristics and phase composition, both relating to material stability. The project will benefit from access to our experimental facilities: fluidized beds for capture of CO_2, and in-situ Raman, thermogravimetry and Diffusive reflectance infrared Fourier spectroscopy (DRIFTS) for material characterisation during CO_2 capture and release.

This project can be easily extended into a full PhD project, implementing machine learning models (ANN and PCA) to predict possible new directions for materials' improvements and to analyse the large body of experimentally collected data.

Five key words for this project: CO_2 capture, energy, nanomaterials, experiments

Chemistry

(3) The electrolyte design of Zn-ion capacitors for electrochemical carbon capture

Project Supervisor: Dr Alexander Forse

Host Department/Institute: Yusuf Hamied Department of Chemistry

Project Outline:
Anthropogenic carbon dioxide (CO2) emissions are widely recognised as the primary contributor to global warming and climate change (Nat. Energy 7, 1065-1075, (2022)). Efficient CO2 capture from point sources is one critical approach to promoting the following CO2 storage and utilisation towards net zero emissions (Chem. Rev. 123, 8069-8098, (2023)). This internship project will delve into the innovative realm of electrochemical CO2 capture, a technology with improved energy efficiency and complementary role to conventional CO2 capture methods (Chem. Soc. Rev. 51, 8676, (2022)).

Our exploration focuses on developing Zn-ion capacitors, a hybrid electrochemical system of battery and supercapacitor, which exhibits unexpected function of CO2 capture during electricity storage. Based on the unique advantages of Zn-ion capacitors such as enhanced energy and power densities, cost-effectiveness, safety and sustainability (Adv. Energy Mater. 11, 2100201, (2021)), Zn-ion capacitors hold a promise to revolutionise electrochemical CO2 capture technologies. However, the parasitic reactions, particularly electrolyte decompositions, within Zn-ion capacitors are one of the main challenges limiting their stability. Therefore, this internship project aims to design and optimise Zn-ion capacitor electrolytes to suppress parasitic reactions, widen voltage window and elevate both energy storage and carbon capture performance. Join us in pushing the boundaries of innovation for a greener, sustainable future.

1) Week 1: Project launch.
The student will evaluate available electrolyte options for Zn-ion capacitors (e.g., Zn formate-based aqueous electrolytes, Zn acetate-based aqueous electrolytes, Zn gluconate-based aqueous electrolytes, ZnTFSI-based water-in-salt (WIS) electrolytes, etc.) according to the reported literature. A comprehensive comparison of previous electrolyte studies will be conducted to inform the selection process.
2) Week 2-3: Electrolyte preparation and characterisation.
The student will select a series of suitable electrolytes and then prepare them in the laboratory. The essential physicochemical properties of those electrolytes including ionic conductivity and stability will be characterised in the normal coin cell configuration through electrochemical impendence spectroscopy (EIS) and cyclic voltammetry (CV), which will be potentially beneficial to the following electrochemical CO2 capture testing and performance.
3) Week 4-8: Electrochemical CO2 capture measurement.
Assembling Zn-ion capacitors with selected electrolytes in the custom-made electrochemical gas cell, the student will simultaneously assess their energy storage and carbon capture performance through the galvanostatic charge-discharge (GCD) methods to uncover links between electrolyte compositions, properties and performance. After that, the student will design and optimise a series of novel electrolytes based on the understanding of composition-property-performance correlations, and investigate resulting performance.

Five key words for this project: Energy Storage; Carbon Capture; Electrochemistry; Materials Chemistry; Technology

(4) C–O Activation for C–N Bond Formation

Project Supervisor: Dr Ruth Webster

Host Department/Institute: Yusuf Hamied Department of Chemistry

Project Outline:
During recent investigations we found that an enol ether (PhOCH=CH2) undergoes iron-catalysed C–O bond cleavage in the presence of a silane (H3SiPh) and aryl nitro (ArNO2) compound. The driving force is likely the formation of a strong Si–O bond and the product formed is an ethylaniline (ArNHCH2CH2). This reaction is interesting for three reasons:

I. C–O bond activation is a highly challenging transformation.
II. if we were to use a classical hydroamination approach to form this product, we would need to react ethylene with an aniline: there are few reports of this transformation. Hydroamination typically involves the addition of an N–H bond across an alkene, forming an amine.
III. although reductive amination is the principal route to these types of compounds, we have the opportunity to tune reactivity via catalysis and, for example, functionalise pyrans.
IV. if we consider our future organic feedstocks, they will undoubtedly be highly oxygenation species: our process allows an oxophilic, earth abundant metal (iron) to successfully activate an oxygenated compound under relatively mild conditions.

As part of this project we want to:

a) Optimise the standard reaction: we want to maximise spectroscopic yield of the ethylaniline product, minimise side reactions and provide a good, isolated yield of the ethylaniline once optimisation is complete. Ways to do this include varying concentrations of reagents, varying the reaction temperature and varying the reductant (the choice of silane).
b) Determine the scope of the reaction in terms of nitro functionality (Ar'NO2).
c) Determine the scope of the reaction using a range of enol ethers (ROCR=CR2).

Five key words for this project: Homogeneous catalysis, inorganic/organic synthesis, mechanisms

(5) How do electrolyte properties determine battery energy, power, and cyclability?

Project Supervisor: Dr Svetlana Menkin

Host Department/Institute: Yusuf Hamied Department of Chemistry

Project Outline:
Demand for improved modern battery performance and lifespan continually amplifies to contest with rising green energy storage endeavours and energy utilisation. Battery electrolytes are increasingly growing in importance due to studies showing that their apposite design has a considerable impact on charge rate, capacity fade limitation, and overall safety.

Electrolytes in batteries serve as a medium to transport ions between the electrodes. Although electrolytes are, arguably, the most significant component of the battery, they are also the least studied component. The composition of the electrolyte properties can greatly impact the energy density (i.e., driving range), power (i.e. fast charge and discharge capability), cycle life (i.e., how many cycles the battery will last?), and safety of the battery.

The proposed project aims to develop a methodology to determine dielectric constants for aqueous and organic electrolytes for metal-ion batteries. Electrochemical impedance spectroscopy (EIS) will determine the charge transport mechanism and measure the dielectric constants of the investigated electrolytes. The charge transport in a battery involves electronic transport in the electrodes and ionic transport across the electrolyte. The dielectric constant is a frequency-dependent measure of the ability of a substance to store electrical energy in an electrical field.

Depending on the intended use, electrolytes can be composed of aqueous or organic solvents but typically always have a metal-ion salt dissolved (e.g., electrolytes for zinc- ion and lithium-ion batteries, respectively). Their multicomponent nature, ranging from two to up to four components in more novel systems and their air and moisture sensitivity have made their characterisation challenging.

The student would use a potentiostat in the argon glovebox. Beginning from substances with known dielectric constants and then onto individual electrolyte components, the project's main focus is studying multicomponent electrolytes used in batteries. Success would create a new characterisation and screening method for electrolytes.

These methods can be developed for studying various metal-ion battery systems with the potential to be employed in academic and industrial research. The student will be able to learn some capabilities of EIS, a technique not widely known with confidence but highly valued. More broadly, electrochemical systems experience is invaluably relevant due to the growing demand for energy storage experts.

Five key words for this project: battery, electrolytes, spectroscopy, lithium, dielectric constant

(6) Pyrolyzed 3D Carbon Electrode for Biophotovoltaic Devices

Project Supervisor: Dr Jenny Zhang

Host Department/Institute: Yusuf Hamied Department of Chemistry

Project Outline:
Biophotovoltaics (BPVs) is a potential sustainable solar energy conversion solution that works by harvesting bio-electricity from photosynthetic bacteria. Over the past 5 years, electrode design for BPVs has progressed enormously to boost overall current output. Notably, remarkable 3D-printed micropillar indium-tin-oxide (ITO) electrodes were developed by our group that exhibited high surface areas and excellent light management, resulting in the benchmark photocurrent output (245 μA cm–2).[1] However, ideal electrodes for this application are those that can match the sustainability of BPVs whilst also generating high photocurrent output. Carbon is the most earth-abundant of electrode materials, has been demonstrated to be prime electrode materials in a range of electronic applications. However, attempts to prepare high performance 3D carbon-based electrodes or BPV applications have not yet been successful, despite obvious sustainability benefits. The problem: carbon materials exhibit poor light management and the clever use of structure to boost light penetration through the electrode results in poorly conducting electrodes. The printed scaffolds do not exhibit the same high conductivity as pure nano carbon materials (such as graphene or carbon nanotubes).[2]

Approaches to boost conductivity are needed, and pyrolysis is one promising approach to increase the conductivity of printed lowly-conductive carbon paste to highly-conductive 3D geometry. The project aims to investigate (i) how to make printable carbon-based pastes to form BPV electrode architectures; and (ii) the relationship between the pyrolysis process and the final structure integrity and electrochemical performance of the electrodes. To this end, material composition-chemical activity relationships will be established, to ultimately lead to the design of high performing 3D carbon electrodes. The physical and electrochemical properties will be characterized using a range of techniques, including scanning electron microscopy, 4-point conductivity, and cyclic voltammetry.

The student will be involved in all parts of the material development process, from paste preparation, 3D printing through a state-of-the-art extrusion 3D printer (Bio-plotter), pyrolysis of the printed electrodes, and electrode characterization. The main part of this project will be carried out at The Yusuf Hamied Department of Chemistry. The electrical conductivity performance will be the Microelectronics Research Center. By the end of this highly interdisciplinary project, the student would have been exposed to a diverse range of engineering techniques, light cell culture techniques and electrochemistry.

Reference
[1]. Chen, X. et al., Nat Mater 21, 811–818 (2022).
[2]. Wey, L. T. et al., ChemElectroChem 6, 5375–5386 (2019).

Five key words for this project: pyrolysis, carbon, biophotovoltaic, electrochemistry, 3D printing

(7) Summer Internship In the Organic Chemistry Laboratory

Project Supervisor: Dr Pawel Dydio

Host Department/Institute: Yusuf Hamied Department of Chemistry

Project Outline:
Applications are invited for internships based in Yusuf Hamied Department of Chemistry, University of Cambridge, supervised by Dr. Pawel Dydio, to work on fully funded projects in the field of synthetic organic chemistry and catalysis.

Depending on the intern's background and interests, the project will be focused either on developing and understanding new multi-catalytic systems embedding cooperative reactions into artificial metabolic-like networks or mechanistically driven discovery of new valuable catalytic transformations and addressing the limitations of key catalytic processes by elucidating their mechanistic features.

For recent articles from the Dydio group that provide background, see: Nature Catal. 2019, 2, 114, Chem Catal. 2022, 2, 762, J. Am. Chem. Soc., 2020, 142, 18251, and Angew. Chem. Int. Ed. 2022 (e202116406).

Five key words for this project: organic synthesis, homogenous catalysis, transition-metal complexes, reaction development, mechanistic understanding

Computer Science and Technology

(8) Rust Programming for a New Proof Assistant

Project Supervisor: Professor Jamie Vicary

Host Department/Institute: Department of Computer Science and Technology

Project Outline:
Rust is an exciting modern programming language which can be compiled both to native code and WebAssembly.

In this project you will use the Rust programming language to contribute to the web-based proof assistant <homotopy.io>, working on important sub-systems include server integration and layout code. This project would be particular appropriate for students who have taken a course in category theory, although this is not required.

Five key words for this project: Programming, rust, web programming, category theory

(9) Using large language models for reasoning on visual tasks: the case of the Abstraction and Reasoning Corpus

Project Supervisor: [Dr Soumya Banerjee]

Host Department/Institute: [Department of Computer Science and Technology]

Project Outline:
For half a century, artificial intelligence research has attempted to reproduce the human qualities of abstraction and reasoning - creating computer systems that can learn new concepts from a minimal set of examples, in settings where humans find this easy. While specific neural networks are able to solve an impressive range of problems, broad generalisation has proved elusive. Neural networks require expansive training data to adapt to new tasks, and fare poorly in real-world situations outside their training data.

In this project, we will look at several novel approaches for solving the Abstraction Reasoning Corpus (ARC), a dataset of abstract visual reasoning tasks introduced in 2019. Despite three international competitions with $100,000 in prizes, the best algorithms still fail to solve a majority of ARC tasks. The best solvers today rely on complex hand-crafted rules, without using machine learning at all. We will use recent advances in large language models on this task.

The broad goal of this project is to enable large-language models to reason and generalize in extremely hard reasoning and abstraction tasks (which are traditionally thought to be the domain of human experts only).

This project will also involve injecting more logic and human-like priors in large language models.

Five key words for this project: machine learning, human-like computation, reasoning and abstraction in machines, large language models

(10) Detecting Mood Change and Loneliness in Human-Robot Conversation

Project Supervisors: Dr Guy Laban, Professor Hatice Gunes and Dr Micol Spitale

Host Department/Institute: Department of Computer Science and Technology

Project Outline:
In the realm of human-robot interaction, understanding and detecting the emotional states of individuals engaging with social robots are crucial for enhancing the overall user experience and users' well-being. Prior research has established that the emotional connection and rapport between humans and robots play a pivotal role in the effectiveness of such interactions. Accordingly, social robots' capacity to accurately perceive and respond to changing moods and feelings of loneliness can significantly impact the success of the interaction.

This project endeavours to design and implement deep learning models capable of real-time detection of mood and loneliness during conversational human-robot interactions. We aim to achieve this by leveraging multimodal data sources, including facial expressions, vocal expressions, and the content of the conversation itself.

To facilitate the development of these models, we will utilise two distinct datasets, both obtained through long-term user studies with participants communicating with the social robot Pepper (SoftBank Robotics) for 5 weeks (10 sessions in total). The first dataset comprises interactions between 39 participants, while the second dataset involves 34 participants. In these studies, participants were engaged in various conversations, allowing us to capture a diverse range of emotional expressions and conversational dynamics. Before and after each interaction with the robot, participants answered a questionnaire reporting their mood before and after the interaction, their feelings of loneliness, and other relevant emotional indicators throughout the interactions.

Project objectives:
Implement state-of-the-art deep learning models to enable the ongoing detection of mood fluctuations and loneliness indicators in human-robot conversation.

Innovate and develop novel neural network architectures specifically tailored to capture and represent the nuanced aspects of mood and loneliness in conversational human-robot interactions.

Essential knowledge:
Machine learning and deep learning basic knowledge
Python coding (pytorch, tensorflow, keras libraries knowledge is recommended)

Relevant works:
Laban, G., Kappas, A., Morrison, V., & Cross, E. S. (2023). Opening Up to Social Robots: How Emotions Drive Self-Disclosure Behavior. 2023 32nd IEEE International Conference on Robot and Human Interactive Communication (RO-MAN). https://doi.org/10.1109/RO-MAN57019.2023.10309551
Laban, G., Kappas, A., Morrison, V., & Cross, E. S. (2023). Building Long-Term Human–Robot Relationships: Examining Disclosure, Perception and Well-Being Across Time. International Journal of Social Robotics. https://doi.org/10.1007/s12369-023-01076-z
Laban, G., Morrison, V., Kappas, A., & Cross, E. S. (2023). Coping with Emotional Distress via Self-Disclosure to Robots: Intervention with Caregivers. PsyArxiv. https://doi.org/10.31234/OSF.IO/GBK2J

Five key words for this project: Human-robot interaction, machine learning, deep learning, affective computing, mental health

(11) Equipping Large Language Models (LLMs) with Affective Computing Skills

Project Supervisor: Dr Guy Laban and Professor Hatice Gunes

Host Department/Institute: Department of Computer Science and Technology

Project Outline: LLMs are revolutionising human-computer interaction, presenting unprecedented opportunities for social interaction research. Lexi, an LLMs experimentation interface created in the Cambridge AFAR Lab, is a platform that enables researchers to explore these possibilities. Using Lexi researchers can design and conduct user studies with LLM-powered chatbots, while collecting video and audio data from users. We invite a student to work on the simulation and/or analysis of user affect and expression capabilities of the Lexi platform.

This project aims to equip Lexi with features to capture and analyse user expression and affect displayed during human and LLM-based agent interactions, focusing on enhancing Lexi's toolkit in the following areas:

Expression and Affect Recognition Enhancement: Incorporate real-time expression and affect recognition by integrating open source toolkits like LibreFace into Lexi. This enhancement should focus on analysing user facial expressions, vocal tones, and language patterns to predict affect in terms states/categories (e.g., surprise) or dimensions (e.g., positive or negative) leveraging the capabilities of these existing frameworks to augment Lexi's affective computing abilities.

Conversational Sentiment Analysis Expansion: Enhance Lexi by integrating open source tools for sentiment analysis. This feature will evaluate the sentiment in both Lexi's responses and user inputs, uncovering the emotional nuances of their interactions.

Personality Configuration Tool: Develop a feature for Lexi that lets researchers input Big Five personality scores, which will dictate Lexi's conversational style and responses based on these predefined personality metrics.

Affective Data Visualization Dashboard: Construct an interactive visualisation dashboard, utilising open source tools, to graphically display emotional cues and sentiments. This dashboard should effectively map out the emotional trajectory of conversations alongside user interaction logs, offering researchers a vivid and accessible view of the emotional landscape within the dialogue. This project will leverage Lexi's modular architecture and utilise existing libraries wherever possible to expedite development. A hybrid approach could be implemented, combining existing open-source libraries with customised algorithms tailored to the specific needs of LLM interactions. The intern can choose to focus on some of the objectives/tasks and the intern is not expected to take on all of these tasks within the two month internship.

Essential Knowledge:
We seek an enthusiastic and curious undergraduate with a strong background in computer science, particularly:

- Programming skills in node.js and react.
- Programming skills in Python and experience with pytorch, tensorflow, keras libraries is recommended.
- Understanding of machine learning and deep learning fundamentals and basic AI concepts.

Five key words for this project: Large Language models, affective computing, AI, machine learning, computer vision

(12) Fluid: A Programming Language for Transparent, Self-Explanatory Research Outputs

Project Supervisor: Dr Roly Perera

Host Department/Institute: Department of Computer Science and Technology

Project Outline:
This is an exciting opportunity to work on a new programming language designed to make climate science more open, intelligible and accessible.

Charts and other visual summaries, curated by journalists and scientists from real-world data and simulations, are how we understand our changing world and the anthopogenic sources of that change. But interpreting these visual outputs is a significant challenge, even for experts with access to the source code and data. Fluid (f.luid.org) is a new kind of "transparent" programming language, being developed at the Institute of Computing for Climate Science in Cambridge, that can be used to create charts and figures that are linked to data so that a user can interactively discover what visual elements actually represent.

Fluid incorporates a bidirectional dynamic dependency analysis into its runtime, allowing it to track dependencies as outputs (such as charts) are computed from data. It uses this information to automatically enrich rendered output with interactions allowing a reader to explore its relationship to data, directly through the artefact itself. Fluid builds on so-called "program slicing" techniques based on Galois connections, a neat mathematical abstraction which characterises exactly the relationship between sets of inputs and sets of outputs which depend on them.

Your internship could go in a number of directions, depending on your interests. If you have an interest in programming languages, you could extend Fluid into a literate programming tool, by adding Markdown support and the ability to embed computational content via a Lisp-style backquote mechanism. If your interests are more mathematical, you could add multidimensional arrays to the language, along with various array operations inspired by linear algebra and an extension of the dependency analysis to these new operations.

You will get to present your work to researchers and data scientists at the ICCS and The Alan Turing Institute, and work with PhD students at Cambridge and Bristol. A strong background in functional programming, maths and/or science is a must.

Five key words for this project: programming languages; program analysis; climate science; transparency; data visualisation

(13) Neural Network to WASM Compiler

Project Supervisor: [Dr Tobias Grosser]

Host Department/Institute: [Department of Computer Science and Technology]

Project Outline:
The aim of this 8-week internship project is to implement a WebAssembly [0] + WebGPU [1] backend for ONNX [2], suitable for executing neural networks defined in machine learning frameworks such as PyTorch and TensorFlow in a platform-independent way. One of the questions that this project will aim to answer is whether an automated compilation approach that targets these APIs could yield similar performance to that achieved by Tensorflow.js and ONNX Runtime Web. Our recent investigations in compiling neural networks to hardware accelerators have shown that semantic knowledge about the high-level operations used in machine learning frameworks can be leveraged to generate code competitive with expert-written assembly, and much faster than that generated by general-purpose compilers. The aim of this project would be to investigate the efficacy of this approach when targeting WebAssembly and WebGPU, two platform-independent APIs supported by modern web browsers.

One possible method of compiling ONNX kernels to WebAssembly is by lowering through MLIR [3] and LLVM [4]. LLVM has an existing WebAssembly backend, used by projects such as Emscripten [5]. LLVM comes with many optimisations that are leveraged by the WebAssembly backend, and also with a number of downsides. One downside of this approach is that many of the optimisations in LLVM are tuned for hardware targets, not stack machines such as WebAssembly, which are intended to be interpreted or run with a JIT compiler. Another disadvantage is LLVM's complexity. xDSL [6] is an open-source compiler framework written in Python and developed by Tobias Grosser's research group at the University of Cambridge. It is a reimplementation of MLIR, a compiler framework popular for compiling machine learning kernels. xDSL is developed with ease of exploration and iteration speed as one of the main objectives, in contrast with LLVM's purpose for use in production environments. WebAssembly and WebGPU targets implemented in xDSL would provide researchers with infrastructure to easily implement and test alternative compiler transformations.

Some possible objectives for this project:
A representation of WebAssembly bytecode in xDSL
A representation of the WebAssembly textual format in xDSL
Translation between the two
A translation from the builtin abstractions to WebAssembly
A minimal execution environment for benchmarking programs in WebAssembly format
A comparison of execution characteristics of neural networks compiled through MLIR+LLVM vs their own xDSL-based implementation
A comparison of execution characteristics of neural networks executed with Tensorflow.js and ONNX Runtime Web and their own implementation
[0]: https://webassembly.org/
[1]: https://developer.mozilla.org/en-US/docs/Web/API/WebGPU_API
[2]: https://onnx.ai/
[3]: https://mlir.llvm.org/
[4]: https://llvm.org/
[5]: https://emscripten.org/
[6]: https://xdsl.dev/

Five key words for this project: Compilers, WebAssembly, Machine Learning, WebGPU

Engineering

(14) Flexible Self-healing Ion Gel Battery

Project Supervisor: Dr Tzia Ming Onn

Host Department/Institute: Energy, Fluids and Turbomachinery, Department of Engineering

Project Outline:
Advancements in energy storage is paramount in reducing our over reliance on non-renewable carbon sources. The current generation of batteries and supercapacitors rely on liquid electrolyte as a medium for charge transport between the cathode and anode. However, liquid electrolytes pose safety concerns related to flammability and chemical instability, and its high internal resistance limits the charging rate in the minute time scale. Solid state Li+ inorganic electrolytes improve on liquid electrolytes in terms of internal resistance and safety, but its implementation into commercial systems is severely limited by its electro-mechano-stability related to dendrite formation/high current leakage.

This project will explore a different class of semi-solid/solid electrolytes called ion gels. Ion gels can be self-healing, and they should be able to withstand structural stresses from extended operations. This project will involve synthesizing and measuring the electronic properties and durability of these polymer-based gels over extended operations.

Five key words for this project: Energy Storage, Solid State, Ion Gel, Stability, Self-healing

(15) High-speed Flow Measurement Equipment Controls

Project Supervisor: Professor Holger Babinsky

Host Department/Institute: Energy, Fluids and Turbomachinery, Department of Engineering

Project Outline:
The aerodynamics lab has two supersonic wind tunnels which use a variety of diagnostics to measure flow properties. These include a computer-controlled 3-axis traverse system as well as pressure scanners and laser-based systems. At present the traverse gear and its integration with the other diagnostics is controlled via various scripts running Labview on an old computer. We have purchased upgraded equipment (eg motors) for the traverse and would like to develop a new control system from scratch using Matlab.

The project involves the development of the new control system to programme the traverse motion, complete with user-friendly front-end. In addition, it is hoped that the new system can also control the data acquisition hardware to arrive at an integrated Matlab-based future-proof solution. The intern should be very competent with programming and Matlab and have experience in hardware/software integration and stepper motors. Apart from the existing equipment, there is a budget to purchase any necessary additional items. The project will be mentored by several current PhD students (who use this equipment). The aero-lab is an active place of research and the project offers an opportunity become an integral part of our on-going high-speed flow investigations.

Five key words for this project: measurement technology, matlab, data acquisition, control, aerodynamics

(16) Unification of codebases for biosignal processing and development of interactive interface using Python

Project Supervisor: Dr Amparo Güemes Gonzalez

Host Department/Institute: Electrical Engineering, Department of Engineering

Project Outline:
This 8-week summer internship project aims to improve the accessibility and user experience of existing biosignal processing code by refining its structure and creating an interactive interface using Python. The primary objectives include understanding the current codebases, creating a user-friendly interface, and ensuring seamless integration for an enhanced overall user experience.

Objective 1: Familiarization with Existing Codebase
Begin by gaining a comprehensive understanding of the current biosignal processing codes. Identify and merge key components and document the code structure to pave the way for subsequent enhancements.

Objective 2: Code Refinement
Focus on refining the existing code, when needed, to improve readability and maintainability. Engage in collaborative code reviews with mentor, supervisor and lab peers to incorporate valuable feedback from the team.

Objective 3 : Interface Design and Prototyping
Explore Python libraries/frameworks to design and create an interactive user interface. Prioritize user-friendliness, allowing users to easily input data, configure parameters, and visualize signal processing results.

Objective 4: Integration and Testing
Integrate the refined signal processing code with the newly developed interface. Conduct thorough testing to ensure the seamless functionality and reliability of the integrated system. Address and resolve any identified issues or bugs to deliver a robust solution.

Objective 5: Documentation
Create detailed documentation encompassing the refined code and interface usage instructions. Prepare a final presentation summarizing the project outcomes, emphasizing improvements, and demonstrating the user-friendly interface. Submit the finalized codebase and documentation.

Five key words for this project: Coding, signal processing, python, graphical user interface, signal visualisation

(17) Climate resilient schools: smart building monitoring and outreach

Project Supervisor: Dr Rachel Thorley

Host Department/Institute: Civil Engineering, Department of Engineering

Project Outline: This outward-looking project aims to reduce energy usage and increase efficiency in schools through smart building monitoring and digital innovation.

This is a great opportunity to get involved with all stages of research and to liaise with external stakeholders. From experimental design, data collection, analysis and communication of findings. With increasing cost of living and commitments to reduce greenhouse gas emissions by at least 80% by 2050 relative to 1990 levels, it has never been more important to do everything we can to reduce energy demand. In educational settings, energy usage is high and savings are particularly important for schools, where those in lower income areas. This project aims to identify opportunities to reduce energy demand and keep it low without requiring energy analysts to manually investigate each site individually, at further expense.

This project builds on an outreach programme called Living Lab: Climate Action. For this, 12-15 year-olds from widening participation backgrounds carried out authentic research, analysing data from environmental sensors placed in UK schools to monitor energy use. Pupils interpreted some data to make energy-saving recommendations for their schools, and attended the University of Cambridge for an aspirational university visit including hands-on activities and to present their research. This project aims to connect and extend these findings, to identify patterns and broaden the impact.

Proposed activities:

1) To extend the sensor network in UK schools and educational settings participating in campus energy loss monitoring. This may involve some travel and stakeholder engagement
2) To perform a thorough analysis of data gathered from a variety of school settings to derive knowledge of how, where and when energy is used and inefficiencies.
3) To identify how, when and where energy is used and lost and identify opportunities to reduce and shift demand by comparing differences in energy use over time and by cross-site comparison. To use this to establish a method to identify problems at particular sites and recommend interventions.
4) To develop automated techniques for supporting analysis, identifying and recommending energy savings strategies. We are open-minded about approach to analysis. For a candidate with interest and skills, this could be approached using statistical or machine learning techniques.
5) To communicate findings and make a real impact!
    a. Creating and testing resources to support schools, teachers and/or pupils
    b. Contribute to writing a research article for conference or journal publication
    c. Opportunity to be part of the facilitator team or try leading a session at a STEM outreach residential for Y12 pupils this summer.

We are looking to recruit several summer interns on related STEM and widening participation projects, and link with Cambridge Zero's summer research intern network, which will provide opportunities for socialising and meeting new friends this summer! With a broad scope, there is much opportunity to choose your own path and specific focus for this project.

Five key words for this project: Decarbonisation, Energy Efficiency, Smart sensors, Data, Outreach

(18) Effects of virtual reality and AI deployment in scenario planning

Project Supervisor: Dr Letizia Mortara

Host Department/Institute: Institute for Manufacturing, Department of Engineering

Project Outline:
This project will study the integration of Virtual Reality (VR) Augmented Reality (AR) technologies in enhancing in decision making processes. Specifically, the student will collaborate with the team who are building a tool which integrates these technologies in scenario planning exercises. Scenario Planning is an approach that supports organizations in the development of strategies. It is used to consider possible future events so companies can develop long-term plans for circumstances where there is much uncertainty (e.g. to decide how to cope with the consequences of climate change).

Through the deployment of the new tool in the real world, the student will explore the effects the technology have on decision-makers, in terms of behaviour, easiness of of use, support in developing the decision.

Five key words for this project: VR, AI, AR, Scenario planning, Programming, Experiments, Interviews

(19) Using Mobile Augmented Reality for Guiding Multicopter Drone Attachment to Payload

Project Supervisor: Dr Thomas Bohné

Host Department/Institute: Institute for Manufacturing, Department of Engineering

Project Outline:
Recently, a novel approach has been proposed for transporting parcels of different sizes and weights using a reconfigurable multicopter drone. The key innovation is using a modular design, where the parcel becomes the drone's main body, and individual propulsion modules with motors, propellers, batteries, and electronics can be attached to its edges as needed. Such an approach increases flexibility as a single drone can transport various parcels, eliminating the need for a fleet of specialised drones. It also warrants more efficient use of resources, as only the necessary propulsion modules are used for each flight. Furthermore, the system is relatively simple and inexpensive to manufacture, making it a cost-effective solution for parcel delivery.

However, we need to simplify the presently complex drone placement and attachment procedures to become a viable alternative to the current delivery methods. Here, we can use mobile Augmented Reality (mobile AR) facilitated with a smartphone or other mobile device for visual guidance. For example, we can use a mobile device to scan the payload and AR to show the multicopter's docking points overlayed on the package, highlighting the precise attachment locations. Furthermore, with AR-based interactive real-time feedback, we can guide the user through the attachment process, simultaneously verifying its progress, thus mitigating potential errors. The developed system can be evaluated with human participants in a controlled user experiment as part of the project. If successful, the project is intended to lead to scientific publication.

Five key words for this project: multicopter drone, augmented reality, AR, mobile AR, drone-to-payload attachment

(20) Using Augmented Reality and Gestural Input to Operate Unmanned Aerial Vehicles

Project Supervisor: Dr Thomas Bohné

Host Department/Institute: Institute for Manufacturing, Department of Engineering

Project Outline:
Within the project's scope, we plan to investigate the possibility of controlling an Unmanned Aerial Vehicle (UAV drone) with the help of mixed input methods such as voice, gestural and eye-gaze-based techniques. The latter's input capabilities will be facilitated with the help of an Augmented Reality (AR) headset. The AR interface belongs to the group of so-called immersive interfaces that provide users with an enhanced feeling of interacting with virtual objects as they would be physically present in the same cyber-physical space. In the case of AR, this effect is achieved by blending digital artefacts within the user's field of view. Furthermore, the AR state-of-the-art headsets possess the ability to track and recognise hand gestures as well as track eye gaze and head movements. Thanks to these unique characteristics, AR can also serve to visualise the intended trajectory of the drone movement and any other relevant information.

The project aims to investigate whether using AR to facilitate drone control offers a suitable and efficient alternative to current practice in UAV operation via specialised controllers. As part of the project, we plan to develop a proof-of-concept prototype system where AR and drones are coupled so the information and data between one and the other can be exchanged bi-directionally. The developed system can be evaluated with human participants in a controlled user experiment as part of the project. If successful, the project is intended to lead to scientific publication.

Five key words for this project: drones, augmented reality, AR, drone control, gestural input

(21) Using Augmented Reality to Guide Manual Assembly of Origami Robots

Project Supervisor: Dr Thomas Bohné

Host Department/Institute: Institute for Manufacturing, Department of Engineering

Project Outline:
Origami robotics utilises the ancient art of paper folding to create soft robots made from flat sheets of paper or other materials that unfold and morph into complex shapes and can be enhanced with electronic components. However, folding an intricate origami robot can be a daunting task. Traditional instructions often rely on two-dimensional diagrams and paper-based instructions. Here, we plan to exchange these classical non-interactive instructions with real-time digital guidance achieved with the help of Augmented Reality (AR) technology.

This immersive interface allows for blending digital artefacts, such as textual imagery of video-based content within the user's field of view. Thus, we can use AR to overlay precise step-by-step instructions concerning manual origami robot folding onto the user's workspace. For instance, animated arrows can trace the folding lines, 3D models show the desired state of the folded paper sheet, while virtual hands demonstrate each crease with practised ease. Moreover, thanks to the possibility of deploying a headset with state-of-the-art onboard computer vision models, the AR head-mounted display (HMD) can track and verify progress and provide real-time feedback to its users. To that end, we want to prototype an AR solution to help guide its user in folding and building an origami robot.

As part of the project, the developed system can be evaluated with human participants in a controlled user experiment. If successful, the project is intended to lead to scientific publication.

Five key words for this project: origami robotics, augmented reality, AR, computer vision, edge computing

(22) Large-scale experiment and fluid dynamic simulation of the falling paper problem

Project Supervisors: Professor Fumiya Iida and Dr Yue Xie

Host Department/Institute: Bio-Inspired Robotics Lab, Information Engineering, Department of Engineering

Project Outline:
The falling paper problem can be dated back to the work of James Clerk Maxwell, where he investigates the rotation and the drift direction of a tumbling card when this card falls from high above to the air. The fluid mechanics behind grants the paper with complex falling behaviors, and the map between paper shape and falling behavior becomes a interesting and complicated research topic. In robotics domain, shape design is a fundamental problem which significantly influences the robot performance. Therefore, we take the falling paper problem as a case study for robot shape design, which helps the robot behave in complex environments. We aim to figure out a general strategy for robot design by doing large-scale experiments or dynamic simulations.

We have established an experiment set-up which is able to automatically create papers with different shapes, drop papers, and extract falling behaviors. Students interested in robotics and fluid mechanics are welcome to join.

Five key words for this project: Emergent behavior, robot design, falling paper, fluid mechanics, machine learning

(23) Soft Robotic Walking Fish

Project Supervisor: Professor Fumiya Iida

Host Department/Institute: Bio-Inspired Robotics Lab, Information Engineering, Department of Engineering

Project Outline:
Researchers have been interested in the development of walking locomotion by aquatic animals, which was necessary for ancient fish to leave the water and begin to live on land. Today, there are several species of fish that exhibit walking behaviors both underwater and, for limited periods of time, on land. Using these fish as an example, we propose the creation of a soft walking fish robot to understand how a body plan adapted to life underwater can create walking locomotion.

The student will create a design generally inspired by existing fish species and will use established soft robotics fabrication and control techniques to make a walking robot. Once the robot is made, the student will perform experimental testing to characterize the robot’s performance.

Five key words for this project: robotics, bioinspiration, locomotion, soft material, underwater

(24) Robotic Interpretation of Sheet Music for Piano Playing

Project Supervisor: Professor Fumiya Iida

Host Department/Institute: Bio-Inspired Robotics Lab, Information Engineering, Department of Engineering

Project Outline:
The piano is an intricate instrument that is difficult for humans to master even after years of dedicated practice. Piano playing presents a profound challenge for both musicians and, intriguingly, for robots. In order to mimic the sensory-motor coordination observed in human pianists, robots must endeavor to address the challenge of interpreting the sheet music information and determining the finger movements required to execute keystrokes. This project addresses the challenge of enabling the robot to autonomously understand sheet music.

The objective is to utilize this interpreted musical information as a control signal, guiding a robot arm to execute piano performances on an actual piano. The emphasis is on infusing the robotic piano playing with expressive features such as dynamics and articulation, akin to those exhibited by human musicians. We aim to design an algorithm that can read the musical notations of sheet music, capture the musical cues, and then apply this information to the control of a robot arm to implement piano playing.

We have established an experimental setup that is able to perform piano keystrokes with designated velocity, tempo and rhythms. Students interested in artistic robots and control are welcome to join.

Five key words for this project: Piano playing robot, sheet music, robotic interpretation, robot control, coordinated keystrokes

Geography

(25) Curriculum Development for Sustainability for the Third Pole Cryosphere Region

Project Supervisor: Professor Michael Bravo

Host Department/Institute: Department of Geography

Project Outline:
The aim of this internship is to create and organise a curriculum of bibliographical resources around the umbrella theme of sustainability for the Third Pole and its wider context. The term 'Third Pole' refers to the Himalayas-Hindu Kush, a region in which upwards of a billion people depend upon the meltwaters from the high-altitude glaciers. The region is also home to a great diversity of cultures and languages, as well as the borderlands of great powers including India, China, and Russia.

The Third Pole is where the cryosphere meets society in all its rich complexity. Its significance is global as well as regional. The logic behind this proposal is a growing recognition of the need for a more joined up understanding of the global cryosphere, bringing together the polar high latitude regions with high altitude mountain regions. In fact policy makers, for example, in the Arctic and Himalayas, have already begun a dialogue about possible lessons to learn comparatively by understanding how lessons in governance and sustainability can be learned through cross-regional comparison.

The Third Pole has a growing place in the School of Physical Sciences' teaching in the Geography Department as well as the Scott Polar Research Institute (as well as programmes outside the school such as Social Anthropology).

Curriculum development is a priority for the successful delivery of our teaching commitment. Existing teaching is popular with our students. Currently no such teaching resource is known to exist. The focus of the curriculum would span public policy development, climate policy, economics, ethics, and public engagement. The project will also include research on applicable consultation procedures with indigenous or local peoples potentially impacted by the melting of the glaciers in the Himalayas.

The project entails three phases:
i) establish a framework structure of sub-topics
ii) carry out extensive bibliographical research to create a database iii) populate modules corresponding to the sub-topics and iv) preparing some guidance for prospective users. The curriculum development can be expected to inform or be incorporated into preparations for our Part 2 Cryosphere and Society paper, our more specialised Third Pole seminars at the M.Phil. level; or it could be used to inform seminars hosted by different organisations.

The internship would be hosted by the Centre for Climate Repair, the Dept of Geography and Scott Polar Research Institute.

Five key words for this project: SDGs, Third Pole, Geography, Curriculum Development

Materials Science & Metallurgy

(26) Colour-tuneable upconversion emission via triplet-triplet annihilation

Project Supervisor: Dr Larissa Gomes Franca (email: lg735@cam.ac.uk)

Host Department/Institute: Department of Materials Science & Metallurgy

Project Outline:
Photon upconversion (UC) is a process wherein a material absorbs two low-energy photons (e.g. infrared) and transforms them into a single higher-energy photon (e.g., visible). This mechanism has become a crucial method for enhancing energy efficiency and finds extensive use in technological applications, including solar energy conversion, optical communication, and various biological functions such as bioimaging and cancer therapy. Notably, triplet–triplet annihilation (TTA) is a method for achieving UC that offers advantageous features like easy colour-tuneability.

During this summer internship, our focus will be on investigating various sensitiser materials that contribute to populating the triplet excited states into the system. The aim is to gain a deeper understanding of the critical parameters that can drive the upconversion emission, e.g. molecular structure, triplet state lifetime, and other parameters. Exploring the roles of sensitisers allows us to comprehend the conversion of lower-energy photons into various higher-energy light, such as blue and green.

Throughout this eight-week internship, the students will engage with a variety of optical spectroscopy techniques, involving both steady-state and time-resolved methods. Furthermore, the student will be involved in collecting, processing, and analysing data. By examining various sensitisers and emitters for UC via TTA, we will understand how to obtain and design efficient photon conversion between these two counterparts.

Five key words for this project: colour-tuneability, photon upconversion, triplet-triplet annihilation, sensitizer materials, optical spectroscopy.

Mathematics

(27) Salt dispersion and mixing in estuaries: laboratory experiments

Project Supervisor: [Dr Adrien Lefauve]

Host Department/Institute: [Department of Applied Mathematics and Theoretical Physics]

Project Outline:
This is an experimental project in environmental fluid dynamics that aims to better understand how salt is dispersed and mixed in estuaries, which is a growing concern in civil engineering. The ultimate goal is to improve mitigation measures and the resilience of coastal infrastructures under sea-level rise caused by climate change.

Estuaries are transition zones where fresh river water meets the ocean's saltwater, and are vital to modern society (most of the world's largest cities are found on estuaries, including Tokyo, Shanghai, New York, Mumbai, and, of course, London). The flow of water and salinity within estuaries affect our water supply, agriculture, fisheries, biodiversity and tourism to name a few. Climate change is expected to impact estuarine dynamics (e.g. through sea level rise, more frequent droughts), but the effects on the circulation and levels of mixing (ultimately setting the salinity levels) are yet unknown. A particularly interesting and important problem is how dense saltwater trapped in topographic depressions ('pits') can be flushed by an in-flow of less dense freshwater. The turbulent entrainment and mixing of the salt will be examined in the laboratory under controlled conditions. The goal is to visualise and quantify the three-dimensional fluid flow and mixing to yield new insights and scaling laws, and compare them to exisiting numerical models and field measurements.

This project would suit a student with a strong quantitative background (mathematics, physics), ideally with an introductory fluid dynamics course or equivalent. The project will take place in DAMTP's G. K. Batchelor Laboratory, hence a willingness to tinker with experimental apparatus and carry out simple experiments with relative independence is expected.

Five key words for this project: estuaries, sea-level rise, turbulence, fluid dynamics, coastal engineering

(28) The evolution of microbial cooperation in space

Project Supervisor: [Dr Nuno Oliveira]

Host Department/Institute: [Department of Applied Mathematics and Theoretical Physics]

Project Outline:
It has been argued that bacteria rely on other strains and species to grow as they often lose important genes that code for leaky traits they can acquire from other genotypes, and that this adaptive gene loss could be a route for the evolution of microbial cooperation (1). However, current evolutionary theory predicts that competition dominates microbial interactions and that mutual dependencies between microbial genotypes are rare, particularly in spatially heterogenous environments where it is harder for microbial genotypes to find the partners they need for their growth (2). While this theory has found experimental support in the literature, it ignores a key piece of bacterial biology: cell motility and chemotaxis. In natural and clinical settings, bacteria not only display different forms of active motility, ranging from swimming and twitching to swarming, but they can also bias their motion in chemical gradients (chemotaxis).

This project seeks to understand if and how bacterial motility and chemotaxis promote or jeopardize the evolution of microbial cross-feeding. Methodologically, it is expected that the student builds upon our current lattice model for the evolution of within-genotype cooperation and extends the model for interactions between different genotypes. Our current model is a modified version of Reichenbach et all's lattice model, which the authors use to study the effect of motility on biodiversity (4), and we have used it to study how different types of motility affect the evolution of within-genotype cooperation in microbial communities. Once the dynamics of the lattice model for between-genotype cooperation is well-understood, it is expected that the student develops a deterministic version to confirm and extend the results obtained with the stochastic model (5).

(1) Morris JJ, Lenski RE, Zinser ER. (2012) The Black Queen Hypothesis: Evolution of dependencies through adaptive gene loss. MBio 3: e00036-12.
(2) Oliveira NM, Niehus R, Foster KR. (2014) Evolutionary limits to cooperation in microbial communities. Proc Natl Acad Sci USA 111(50):17941-17946.
(3) Oliveira NM, Martinez-Garcia E, Xavier J, Durham WM, Kolter R, Kim W, Foster KR. (2015) Biofilm formation as a response to ecological competition. PloS Biol 13(7).
(4) Reichenbach T, Mobilia M, Frey E. (2007) Mobility promotes and jeopardizes biodiversity in rock-paper-scissors games. Nature 448:1046-1049.
(5) Wakano JY, et al. (2009) Spatial dynamics of ecological public goods. Proc Natl Acad Sci USA 106(19):7910-4.

Five key words for this project: microbial communities, cross-feeding, cooperation, competition, motility

(29) From Theory to Treatment: Advancing Implicit Neural Representations for Healthcare

Project Supervisor: Dr Angelica Aviles-Rivero

Host Department/Institute: Department of Applied Mathematics and Theoretical Physics

Project Outline:
Implicit Neural Representations (INRs) [1,2] signify a revolutionary shift, challenging the conventional grid-based approach to data representation. It employs a continuous coordinate-based function embodied by a neural network, to implicitly encode the discrete data, represented as a mapping function, f: R^n → R^m. Implicitly representing image signals, particularly for medical imaging applications e.g.,[3], has become popular due to its memory efficiency, allowing representation without resolution restrictions. Additionally, the ability to take values in the continuous domain enables unlimited resolution, while effective data usage allows handling reconstruction and synthesis tasks without the need for costly external annotation.

While there is growing interest in applying Implicit Neural Representations (INR) to the medical domain, the current practice is limited to integrating existing nonlinear activation functions into networks tailored for specific tasks in biomedical image analysis. This project aims to elevate the approach by designing a novel nonlinear activation function within the INR framework, aiming to enhance performance across diverse tasks, such as segmentation, reconstruction, and registration in images including MRI and CT.

[1] Sitzmann, V., Martel, J., Bergman, A., Lindell, D. and Wetzstein, G., 2020. Implicit neural representations with periodic activation functions. Advances in neural information processing systems, 33, pp.7462-7473.
[2] Shen, Z., Cheng, Y., Chan, R.H., Liò, P., Schönlieb, C.B. and Aviles-Rivero, A.I., 2023. TRIDENT: The Nonlinear Trilogy for Implicit Neural Representations. arXiv preprint arXiv:2311.13610.
[3] Khan, M.O. and Fang, Y., 2022, September. Implicit Neural Representations for Medical Imaging Segmentation. MICCAI.

Five key words for this project: Deep Learning, Medical Imaging, Implicit Neural Representation

(30) Cosmic Strings and Boson Stars

Project Supervisor: Dr Amelia Drew

Host Department/Institute: Department of Applied Mathematics and Theoretical Physics

Project Outline:
Cosmic strings are a class of topological defect that are predicted by many beyond-the-Standard-Model theories in high energy physics. They are found from cylindrically symmetric solutions to the wave equation for a complex scalar field with a 'wine bottle' potential, and are formed due to a U(1) symmetry breaking. They are a potential source of axion dark matter, as well as gravitational waves. Boson stars are spherically symmetric solitonic solutions of the Einstein-Klein-Gordon equations with a similar potential.

This project will investigate the mathematical links between these two phenomena to determine whether the literature on the two subjects regarding eg. their gravitational wave signatures or massive/massless radiation can be related, with the potential to find new applications.

Five key words for this project: Cosmology, gravity, dark matter, fundamental fields, theoretical physics

(31) The fluid dynamics of smoke-filled vortices in the stratosphere

Project Supervisor: Dr Kasturi Shah and Professor Peter Haynes

Host Department/Institute: Department of Applied Mathematics and Theoretical Physics

Project Outline:
Long-lived rising bubbles of wildfire smoke or volcanic aerosol contained within strong vortices have been observed in the stratosphere. The bubble-vortex structures induce their own circulation by forcing wind and temperature patterns. Heating through absorption of solar radiation has been hypothesised as driving these structures. Our work thus far has modelled the system as two-way interaction between smoke (represented as a heating tracer) and vortex dynamics.

There are several possible avenues for summer research on smoke-filled vortices and we are happy to supervise you on the avenue that most interests you. Possibilities include how the absorptive properties of different aerosols contained within the bubble influence its self-lofting, how smoke plumes self-organise into vortices in 3D configurations, how vortices deform in 3D flows, how bubble-vortex structures are transported by the large-scale circulation, and so on. There is opportunity to align the research approach of this project to skills you'd like to learn, e.g., how to develop "pen-and-paper" theory, how to solve partial differential equations numerically, how to run state-of-the-art fluid dynamics solvers.

To learn more about this recently detected phenomenon, here are a few papers about observations of smoke-filled vortices in the stratosphere:

- Khaykin, Sergey, et al. "The 2019/20 Australian wildfires generated a persistent smoke-charged vortex rising up to 35 km altitude." Communications Earth & Environment 1.1 (2020): 22.
- Kablick III, G. P., et al. "Australian pyroCb smoke generates synoptic-scale stratospheric anticyclones." Geophysical Research Letters 47.13 (2020): e2020GL088101.
- Lestrelin, Hugo, et al. "Smoke-charged vortices in the stratosphere generated by wildfires and their behaviour in both hemispheres: comparing Australia 2020 to Canada 2017." Atmospheric Chemistry and Physics 21.9 (2021): 7113-7134.
- Khaykin, Sergey M., et al. "Unexpected self-lofting and dynamical confinement of volcanic plumes: the Raikoke 2019 case." Scientific Reports 12.1 (2022): 22409."

Five key words for this project: fluid dynamics, atmosphere, applied mathematics, partial differential equations, computation

(32) Deep neural networks in physics-based inverse imaging problems

Project Supervisor: Professor Carola-Bibiane Schönlieb

Host Department/Institute: Cambridge Image Analysis Group, Department of Applied Mathematics and Theoretical Physics

Project Outline:
Inverse problems are concerned with reconstructing unknown model parameters from indirect and noisy measurements and arise in practically all imaging applications. In the last decade, thanks to deep learning, processing of imaging data has undergone a paradigm shift from knowledge driven approaches, deriving imaging models from first principles, to purely data driven approaches, instead deriving models from data. Most inverse problems of interest are ill-posed and require appropriate mathematical treatment for recovering meaningful solutions and while purely data-driven learning have been able to achieve remarkable empirical success for image reconstruction, they often lack rigorous reconstruction guarantees. Of particular interest are therefore methods that operate at the interface of these paradigms and feature both a knowledge driven (mathematical modelling) and a data driven (machine learning) component.

The precise details of the project will be tailored to the students interest and skill set, but possible topics/projects for investigation include:

1. Acquisition (operator)-aware learned reconstruction
    - Xia, Wenjun et al. “CT Reconstruction With PDF: Parameter-Dependent Framework for Data From Multiple Geometries and Dose Levels.” IEEE transactions on medical imaging vol. 40,11 (2021): 3065-3076. doi:10.1109/TMI.2021.3085839
    - Adler, Jonas, and Ozan Öktem. "Solving ill-posed inverse problems using iterative deep neural networks." Inverse Problems 33.12 (2017): 124007.
2. Combining physics informed neural networks with learned regularisation
    - M. Raissi et al. "Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations." Journal of Computational Physics, https://doi.org/10.1016/j.jcp.2018.10.045.
    - Mukherjee, S., Dittmer, S., Shumaylov, Z., Lunz, S., Öktem, O., & Schönlieb, C. B. (2020). "Learned convex regularizers for inverse problems."
    - Berk, Aaron, et al. "Deep Proximal Gradient Method for Learned Convex Regularizers." ICASSP 2023-2023 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). IEEE, 2023
3. Structured non-convex learned regularisation
    - Mukherjee, S., Dittmer, S., Shumaylov, Z., Lunz, S., Öktem, O., & Schönlieb, C. B. (2020). "Learned convex regularizers for inverse problems."
    - Shumaylov, Zakhar, et al. "Provably Convergent Data-Driven Convex-Nonconvex Regularization." arXiv preprint arXiv:2310.05812 (2023).

All of the projects proposed can be pursued from both programming and theory direction, however a level of programming (preferably Python) experience is required. Other than this interest is the only thing needed!

Five key words for this project: Inverse problems, physics-informed neural networks, deep learning, learned reconstruction, learned regularisation

(33) Inequalities between f-divergences

Project Supervisor: Dr Varun Jog

Host Department/Institute: Department of Pure Mathematics and Mathematical Statistics

Project Outline:
f-divergence inequalities constitute a fundamental concept in information theory and probability theory, playing a pivotal role in quantifying the dissimilarity between probability distributions. Developed as a generalization of the Kullback-Leibler divergence, f-divergences provide a versatile framework for measuring the divergence between two probability distributions by incorporating a convex function, denoted as 'f.' This class of divergences includes well-known measures such as the Jensen-Shannon divergence, total variation distance, and the chi-square divergence.

One of their key applications is in statistical hypothesis testing, where researchers leverage f-divergences to assess the dissimilarity between observed and expected distributions, enabling robust inference and decision-making. In recent work by the PI, it was observed that two families of f-divergences -- the Hellinger family and the Jensen-Shannon family -- appear to characterize the sample complexity of hypothesis testing. The PI established some loose inequalities between these divergences that were sufficient for the project on hypothesis testing. This project seeks to improve on these results by establishing tight inequalities between these families of divergences.

Five key words for this project: f-divergence, hypothesis testing, inequalities

Physics

(34) Automatic Segmentation of Cells from Raman Spectroscopy Data

Project Supervisor: [Professor Sarah Bohndiek]

Host Department/Institute: [Department of Physics]/[Cancer Research UK Cambridge Institute]

Project Outline:
We use Raman Spectroscopy (RS), which is a non-destructive spectroscopic technique, to analyse the molecular composition of tissue. The imaging technique works by shining a laser beam onto a sample. A small fraction of these samples is inelastically scattered due to molecule vibration and can either increase or decrease the photon energy (referred to as anti-Stokes and Stokes scattering). When a light beam's energy changes, it changes its associated wavelength (colour), which we can detect. These changes are then visualised as a Raman Spectrum and molecules have a unique fingerprint and can directly relate to the structure and functional properties of the imaged tissue.

In our lab, we use this technique to take microscopic images of cells that are affected by cancer. These images are spatially resolved by raster-scanning the cells and taking a full Raman spectrum at each spatial location. Our primary focus is on quantifying and imaging intracellular fumarate, a molecule normally generated during the cellular processing of glucose. Notably, specific mutations in a key enzyme within the Krebs cycle, called fumarate hydratase (FH), can lead to the aberrant accumulation of fumarate. Loss of FH and fumarate accumulation is principally associated with hereditary leiomyomatosis and renal cell cancer (HLRCC), one of the most aggressive forms of renal cell carcinoma. We aim to use RS to unveil the distributions of fumarate in live cancer cells, which can help us elucidate the mechanisms through which fumarate accumulation contributes to cancer.

One part of the analysis is to manually segment the cells from the background in our images. This is a laborious, error-prone and time-consuming process. In this project, you will be tasked to use the Python programming language to implement a deep learning-based program that can do this segmentation.

During the project, you will learn about deep learning, cancer biology, and medical imaging, specifically RS, but also hyperspectral imaging and photoacoustic imaging by interacting with other researchers in the lab. Your day-to-day supervisors will be Dr Janek Grohl, who is a postdoc with a background in computer science working with deep learning on Medical Imaging, and Seema Bachoo, a PhD student with a background in microbiology who is an expert in RS.

Five key words for this project: Medical Imaging, Raman Spectroscopy, Deep Learning, Data Science, Cancer Biology

(35) Geometric and dynamical interpretation of topological invariants

Project Supervisor: Dr Nur Ünal

Host Department/Institute: Department of Physics

Project Outline:
The synergy between topology and physics has revolutionised the way phases of matter are classified in physics in recent decades by offering extremely robust and resilient observables in the form of integer or fractionally quantized responses. Connection to the mathematical realm of topology is the source of this extreme resilience, where the topological invariants are quantized precisely like the number of holes in an object. These concepts take power from the underlying notion that our world is eventually geometric, and so is quantum mechanics.

The Chern number is a paradigmatic example of a topological invariant, which can be measured in experiments of ultracold atomic gases and quantum simulators in two and even four dimensions. Since it lies at the heart of various fundamental topological phenomena, its dynamics and geometrical understanding have been attracting a lot of attention. Our group has recently developed a geometric characterization of multi-level quantum systems in terms nested spheres, which brought a new geometric interpretation of the first Chern number. This project will theoretically investigate extending these geometric descriptions to other topological invariants in higher dimensions, analyzing the connection of higher dimensional spaces and topological invariants. Moreover, going beyond equilibrium settings, these topological invariants and their geometric characterisation can result in novel dynamical responses such as under quantum quenches as will be explored in the project.

Five key words for this project: Topology, quantum mechanics, Chern number, ultracold quantum gases

(36) Physical properties of carbon nanomaterials from supercomputer modelling

Project Supervisor: Mr Bo Peng

Host Department/Institute: Department of Physics

Project Outline:
Carbon nanomaterials possess versatile crystal structures that can be used as a platform for tailoring their electronic and optical properties, as well as their chemical function. As a result, they hold great promise for many technological applications. However, the microscopic mechanisms for the formation of different structural phases of carbon nanomaterials remain elusive. For example, there is no clear explanation for the phase transition from graphite to diamond, which has been known for decades.

In this summer project, the student will explore the structural phases of carbon nanomaterials. This will be accomplished by quantum mechanical modelling techniques using high performance supercomputers. Questions to address include understanding the phase transition using the Landau theory of phase transition, interpreting the role of phonons, etc. If time allowed, there are plenty of open questions around quantum behaviours in carbon nanomaterials, with examples including non-equilibrium dynamics, multi-gap topology and superconductivity.

Five key words for this project: electronic structures, density functional theory, fullerene