1 Summary of proposed exchange activities

A partnership and scientific exchange programme is proposed between the University of São Paulo (USP) and the University of Warwick (UoW). The USP partner is the Institute of Mathematics and Computer Science (ICMC). The UoW partners are the Centre for Complexity Science (CCS) and the Zeeman Institute for Systems Biology and Infectious Disease Epidemiology Research (SBIDER), two interdisciplinary joint ventures of the Warwick Mathematics Institute (WMI). The USP project leader is Prof. Francisco A. Rodrigues, an associate professor and head of the Complex Systems group at the ICMC. The UoW project leader is Dr. Colm Connaughton, a reader in applied mathematics and director of the CCS. The scientific theme is dynamical processes on multi-layer and dynamic networks. It relates to the FAPESP grant "Information spreading in complex networks" (2016/25682-5) held by Prof. Rodrigues. The high level aims of the exchange are:

1. to improve scientific understanding of the dynamics of coherent phenomena in dynamical and multilayer networks.
2. to forge a new and enduring collaboration on complex systems research between UoW and USP.

A detailed description of the scientific objectives of the collaboration is provided in Sec. 3. The proposed exchange programme will run for two years spanning the 2017-18 and 2018-19 academic years. The first year will see visits to UoW by members of the USP team and the second year will see return visits to USP by members of the UoW team. A detailed description of the proposed schedule is provided in Sec. 4. In parallel to this proposal, Connaughton and Rodrigues have jointly prepared a complementary proposal to be submitted to the Leverhulme Trust (deadline 11 May 2017) seeking a Leverhulme Visiting Professorship to be held by Prof. Rodrigues at UoW for the 2017-18 academic year. If funded, this complementary proposal will allow us to significantly enhance both the breadth and depth of the proposed partnership.

2 Description of research team

2.1 Partner institutions

The **Centre for Complexity Science (CCS)** at the UoW was founded in 2007 to host one of the first EPSRC Centres for Doctoral Training (CDT) on the topic of complex systems. It grew rapidly to become one of the largest complexity science research groups in the UK. It currently hosts 8 academic staff, several postdoctoral researchers and about 50 graduate students. It co-hosts the £3.4M EPSRC-MRC Centre for Doctoral Training in Mathematics of Real World Systems in partnership with the **Zeeman Institute for Systems Biology and Infectious Disease Epidemiology Research (SBIDER)** . SBIDER was established in 2016 when the Warwick Systems Biology Centre and Warwick Infectious Disease and Epidemiology Research Centre joined forces to form one of the largest mathematical biology research groups in the UK. It is the coordinating node of a $10M global consortium funded by the Gates Foundation to develop the modelling capability to support the UN 2020 goals for the elimination of Neglected Tropical Diseases. Both the CCS and SBIDER are interdisciplinary joint ventures of the **Warwick Mathematics Institute (WMI)**. WMI ranked 3rd in the UK for mathematical sciences in the 2014 Research Excellence Framework (the most recent UK national research assessment exercise) and 32nd globally in the 2016 QS world university subject rankings. In 2014, Regius Professor Martin Hairer was awarded a fields medal. UoW is therefore ideally placed to participate in and benefit from international partnerships with distinguished researchers like Prof. Rodrigues. USP is an eighty-year old research-led university having the highest QS ranking in Latin America in the last two years. Its **Institute of Mathematical and Computer Sciences (ICMC)** was created in 1971 and is one of the top Brazilian institutions in the fields of computer science, informatics, mathematics, applied mathematics and statistics, for both research and training. ICMC has more than 150 faculty members with an annual peer-reviewed publication output of about 450 papers. The Complex Systems group at ICMC was founded in 2014 and currently hosts 5 academic staff and more than 30 students and post-docs working on complex networks, nonlinear dynamics, control theory and probability.

2.2 University of São Paolo Team

- **Prof. Francisco A. Rodrigues (USP team leader)** is an associate professor at USP. He is the head of the Complex Systems group at the ICMC. His background is in theoretical physics. He has published over 60 papers in leading peer-reviewed scientific journals including Physical Review Letters, Physics Reports and PLoS One with more than 2500 citations to date (Google Scholar). His research specialisation is the interaction between structure and dynamics in the theory of complex networks. His recent work has focussed on the development of concepts and methods for characterisation of complex networks, the study of epidemic and rumour spreading in social and technological networks, the modelling of synchronisation of coupled oscillators and the development of new methods for pattern recognition and data mining. His current and former research students include five PhD students and nine masters students. He has coordinated multiple successful FAPESP projects, including international projects.
- **Prof. Luciano da Fontoura Costa** is a full professor at the Institute of Physics at São Carlos. He holds a degree in Electrical Engineering and a PhD in Physics (Kings College London). He published more than 280 papers in

scientific journal, receiving more than 11,000 citations (h-index 45) (Google Scholar). He advised more than 50 graduate students and coordinated several research projects, including international projects like Human Frontiers. He is an expert in complex networks, image analysis, electronics and data mining.

- **Mr. Thomas Kauê Dal Maso Peron** is a PhD student advised by Prof. Rodrigues. He holds a degree in Physics (2010) and a MSc in computational physics. He has already published over 20 scientific articles, including a paper in Physics Reports. He will finish his PhD course in the second semester of 2017. FAPESP has already approved his post-doctoral fellowship to start this year. He is an expert in synchronization of coupled oscillators.
- **Mr. Guilherme Ferraz de Arruda** holds a degree in Electrical Engineering and MSc in Computer Science. He is finishing the PhD course under the supervision of Prof. Rodrigues. He has published over 10 scientific articles.

2.3 University of Warwick Team

- **Dr. Colm Connaughton (UoW team leader)** is a Reader in the WMI, the director of the CCS and the deputy director of the EPSRC-MRC funded Mathematics of Real World Systems (MathSys) Centre for Doctoral Training. He is an expert on complex systems, fluid dynamics and non-equilibrium statistical mechanics with particular expertise on turbulence and the kinetic theory of irreversible systems. He has published 51 papers in international peer-reviewed journals and is responsible, as PI or CI, for over £11M of current or previous EPSRC CDT support, including the MathSys CDT, plus over £350K of direct research support.
- **Prof. Matt Keeling:** is a Professor of mathematical epidemiology at the University of Warwick with a joint appointment between the Mathematics Institute and the School of Life Sciences. His research focuses on the development and application of mathematical models of infectious disease propagation in human and animal populations. He has authored over 100 papers which have garnered over 11000 citations (Google Scholar). He is currently the director of the Zeeman Institute for Systems Biology and Infectious Disease Epidemiology (SBIDER).
- **Prof. Robert MacKay FRS FInstP FIMA:** is the Professor of Interdisciplinary Mathematics at the Warwick Mathematics Institute, a fellow of the Royal Society and former president of the Institute of Mathematics and its Applications. He is the former director of the Centre for Complexity Science and founding director of the MathSys CDT. He is an expert in dynamical systems, mathematical physics and complexity science. He is particularly well known for his fundamental contribution to the mathematical theory of synchronisation and coherent structures in spatially extended nonlinear systems. He has authored 1 book, 136 peer-reviewed journal articles and 50 other articles, and entered the ISI Highly cited list under Mathematics in 2008.
- **Dr. Samuel Johnson** is an asst. prof. in the WMI and CCS. He is an expert in networks and theoretical ecology.
- **Dr. Louise Dyson** is an asst. prof. in the WMI and SBIDER. Her expertise is in social complexity and epidemiology.
- **Dr. Emre Esenturk** is a Marie Curie postdoctoral fellow in the WMI and CCS. He is an expert in kinetic theory.
- **Dr. Lorenzo Pellis** is a Henry Dale postdoctoral fellow in the WMI and SBIDER. His field of expertise is epidemiology.

3 Scientific objectives

3.1 Background and scientific context

Complex systems are composed of connected elements whose nonlinear interactions give rise to non-trivial collective properties. Commonly quoted examples include our society, the Internet, our brain and cellular interactions. Fundamental research on complexity therefore spans Mathematics, Physics, Biology, Computer Science and Engineering. Policy and technology applications relevant to this project include the control of disease spread in human and animal populations [13] and the control of synchronization in data transmission [18]. In the 1990's it was recognised that many complex systems have a special hierarchical structure: the number of elements with a given connectivity decreases with connectivity in an approximately scale-free way [2]. Networks provide a natural framework for modelling this structure and are thus fundamental in the study of complex systems. Network representations permit investigation of how structural properties of networks affect dynamical processes in the system and the resulting collective properties [3]. To give some examples, the epidemic threshold for disease propagation depends on network heterogeneity and is close to zero in a scale-free network due to highly connected agents acting as super-spreaders. Network structure controls the ability of networks of coupled oscillators, like power grids and brains [1] , to undergo collective synchronisation. Other examples, include cascading failures in engineered systems, percolation in materials and consensus formation in voter models of opinion dynamics.

Until very recently, most research considered static networks with one interaction mode [6]. Most natural and artificial systems however evolve with time and have multiple modes of interaction. As people move from home to work their contacts change. Flocks of birds form complex dynamical patterns across a range of length scales with each bird interacting with a constantly evolving set of neighbours. Such situations are better modelled as dynamical agents moving on a surface, defining interaction networks that change with time [5, 15]. In urban transport systems, people can use and switch between different transport modes. Objects known as multilayer networks [4] can represent these multiple channels of connections, with each layer defining a type of interaction . The study of systems with networks of moving agents and multilayer interactions is thus at the cutting edge of research in the field and there are many open questions to be addressed. This project will answer some of them, building on the combined strengths of the UoW and USP teams. We now list three specific scientific objectives which we will pursue during the project along with the team members whose expertise is required.

3.2 Objective 1: Synchronisation of moving agents (Rodrigues, MacKay, Connaughton, Johnson, Esenturk)

Synchronization occurs when a set of self-sustained oscillators are weakly connected as a network. Network structure influences the emergence of the synchronous state. In the case of Kuramoto oscillators, the critical coupling strength for the emergence of synchronization depends inversely on the second moment of the degree distribution. Most studies on synchronization have considered static networks. However, recently Levis et al. [15] have started to consider oscillators interacting in a dynamic network generated by mobile agents moving in a two-dimensional space and interacting inside a fixed radius. Our goal is to generalize this study to non-flat surfaces. We will implement a model of particles moving in a rough relief whose velocities change according to their positions. Each agent is a Kuramoto oscillator and the interaction between pairs of oscillators occurs according to their distance. This analysis will enable to verify how such terrain affects the emergence of the synchronous state and understand the robustness of the spatial synchronization mechanism identified in [15] . This effort will combine the physical approach to synchronization of Prof. Rodrigues with the rigorous mathematical approach of Prof. MacKay and the expertise of Connaughton and Esenturk on kinetic theory of mass transport models. Dr. Johnson will contribute his experience on complex networks theory and modelling of complex systems.

3.3 Objective 2: Epidemic spreading in dynamic and multilayer networks (Rodrigues, Keeling, Dyson, Pellis)

The study of information propagation on networks has applications to modelling and forecasting the spread of diseases and rumours. Prof. Rodrigues' group have been working with epidemic models on networks for five years [7, 8]. In collaboration with SBIDER researchers Keeling, Dyson and Pellis, we will extend the standard susceptible-infected-recovered (SIR) epidemic model to populations of mobile agents and to populations whose interactions are represented as multilayer networks. In the former case, building on synergy with Objective 1, agents travel in a two-dimensional space and interact when their distance is below a given threshold. A simple variant of such a model has been proposed in [5]. We will extend the approach to include important practical aspects of epidemic dynamics, such as heterogeneous transmission and agents moving with different velocities. Our goal is to understand dynamical processes, such as the epidemic threshold. In the latter case of multilayer representation, our goal is different. We aim to understand how spread of awareness about a disease affects its spread. In one layer, information about a disease is shared among users via a social network. This information affects the transmission of the disease on the other layer of physical contacts. We will improve on previous work [11, 12] by using more appropriate models for information transmission, like the one introduced by Moreno et al. [17].

3.4 Objective 3: Network methods for analysis of turbulence (Rodrigues, Connaughton)

This is the most speculative of our objectives. Recently, several methods have been developed to transform time series into networks [14, 16, 10]. These completely novel approaches to time series have been used to find patterns of activity in dynamical systems such as identification of transition periods in paleoclimate data related to human evolution using recurrence network analysis [9]. We will apply these approaches to Lagrangian timeseries in turbulence. Lagrangian measurements are obtained following the path of a tracer particle in the flow and naturally produce time series. Our hope is to identifying the elusive links between patterns in Lagrangian time series and large scale coherent structures, an issue which is still poorly understood in the turbulence community. While there is no consensus on what is the "best" network representation for a given time series, it is plausible that the ability of network quantities to capture global information about a signal may unveil patterns in Lagrangian data that are invisible to time-local analyses. This aspect of the project will combine Connaughton's expertise in fluid dynamics with Rodrigues' expertise in network theory and pattern recognition.

3.5 Relationship to ongoing FAPESP grant

The associated FAPESP grant "Information spreading in complex networks" (2016/25682-5) is held by Prof. Rodrigues at ICMC. It applies statistical inference to quantify how network properties influence the propagation of information on networks. Details are provided in the attached summary. Objective 2 directly extends this work to spatially mobile populations. Objective 1 is also closely connected since synchronisation results from the spread of dynamical correlations. The project will benefit from the more applied perspective on epidemiology available in SBIDER (Keeling, Dyson, Pellis) and from the more theoretical perspective on synchronisation and statistical physics available in WMI (MacKay, Connaughton, Johnson).

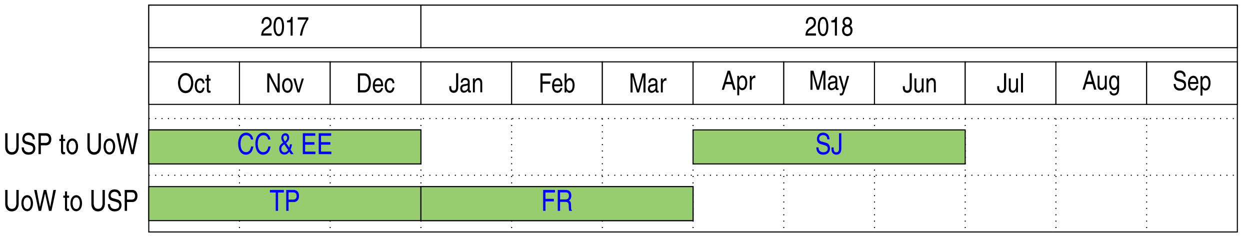
4 Management, timeline and and expected outputs

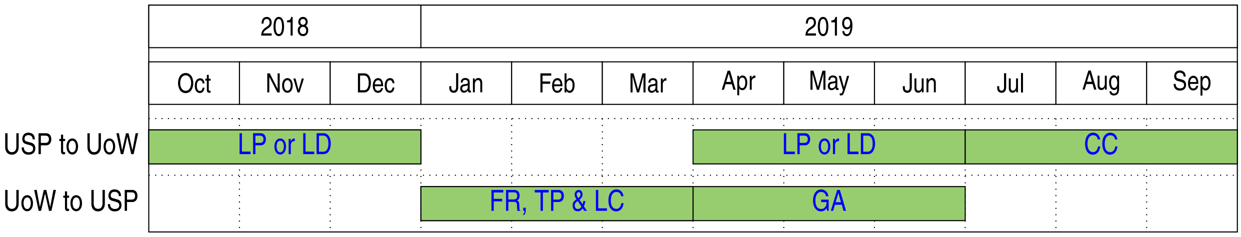
4.1 Management and scientific schedule

The project will be co-managed by Connaughton and Rodrigues following the rules and procedures of UoW and USP. All objectives will be pursued in parallel, since there are many cross-links. An estimated scientific schedule is as follows:

- **Objective 1:** will start with some simulations of synchronization in a two dimensional flat space and build from there. The USP group will implement the software with help of UoW researchers. This will take about three months. Subsequent theoretical analysis will be done jointly and is expected to take about 12 months.
- **Objective 2:** will take about 18 months. Initially, we will adapt the models developed by the Warwick group to multilayer and temporal networks. Next, we will generalize disease transmission models to temporal networks made up of moving agents. Both groups will perform the implementation of the models.
- **Objective 3:** will take about 18 months. The USP group will implement and validate several algorithms to transform time series into networks and apply them to numerical data generated by the UoW group. Then, we will jointly try to determine whether we can learn something about turbulent flows.

4.2 Schedule of exchange visits





In this project schedule, researchers are identified by their initials and bars indicate windows to schedule visits. Flexibility is required given academics' busy diaries. The budget is for visits of two weeks. If the Leverhulme bid succeeds, this schedule will be revised in consultation with FAPESP since Rodrigues would be funded to spend the 2017-18 year at UoW.

4.3 Expected outputs

The following concrete and quantifiable outputs are expected to result from this partnership:

- Scientific publications: collaborative work on the scientific objectives described above will lead to joint publications in high-impact international journals.
- Workshop: Connaughton and Rodrigues hope to co-organise a 2-3 day international workshop on "Dynamics of spatial networks" during Prof. Rodrigues' second visit. This was proposed in response to a recent call for workshop proposals from the EPSRC-funded network on Emergence and Physics Far From Equilibrium, of which Connaughton and MacKay are members. This would be an event of international significance at no additional cost to the grant.
- Training of PhD students: PhD students from UoW's Complexity Science and MathSys CDTs and from USP will also participate in the research described above and enjoy the opportunity for exchange visits between USP and UoW.
- Engagement with wider UK and Brazilian research communities: on the UK side, Prof. Rodrigues will have the opportunity to make seminar visits to complexity science groups at other UK institutions (Manchester, Imperial, Cambridge, Oxford, Bristol, QMUL) to be organised with local seminar organisers.
- Lectures: if the Leverhulme application is successful, Prof. Rodrigues will teach an advanced graduate level course (the Leverhulme Lectures) at UoW consisting of 8 2-hour lectures aimed at graduate students in the Complexity Science and MathSys CDTs. The topic would be "Theory of Networks". They will be delivered via the Mathematics Taught Course Centre (TCC), a joint venture between the maths departments at Bath, Bristol, Imperial, Oxford and Warwick. It uses video-conferencing facilities to organise a series of postgraduate courses each year that can be taken by graduate students at all 5 TCC partners.

5 Impacts of exchange for host and partner institutions

In signing the SPRINT partnership agreement, both UoW and USP have recognised the growing strategic importance of closer scientific relationships between the UK and Brazil. From the perspective of WMI, this partnership has the potential to contribute deeply to the research activities of the CCS and SBIDER. The specialist value that Prof. Rodrigues will bring is his ability to link the more theoretical complexity science and dynamical systems research at Warwick (MacKay, Johnson, Esenturk) with the more applied research being done in epidemiological modelling (Keeling, Pellis, Dyson) and industrial mathematics (Connaughton). At the UK national level, such expertise is particularly important at this point in time as RCUK and the industrial community are increasingly moving towards the view that the significant investments made in complex systems research over the last ten years, including at Warwick, should now be maturing to produce real world applications. The choice of ICMC as a SPRINT partner is therefore strongly aligned both with local research priorities at UoW and with wider national research priorities. The potential benefits will be realised through the outputs mentioned above

From the ICMC side, the collaboration with UoW will reinforce some core ICMC research areas. Researchers at ICMC have experience with theoretical epidemiology, but will benefit greatly from the closeness of the UoW group of Prof. Keeling to real world data and applications. The application of network methods to turbulence data is a novel idea which has the potential to produce something completely new for both groups. UoW also has very complementary theoretical expertise in dynamical systems (MacKay) which will be of value to the ICMC team, Finally, contact with the multi-disciplinary scientific environment at the CCS will greatly improve the scientific experience of younger USP team members.

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