SSM
Scuola Superiore Meridionale

MERC PhD Project Proposal 2023/2024

Title of the research project:

Automatic Detection, Classification and Prediction of Critical Transitions in Network Dynamical Systems: Application to Psychopathology

Keywords (up to five)

Dynamical Systems, Machine Learning, Network Science, Time-Series Analysis, and Psychopathology

Supervisors (at least two from two different areas):

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Project description (max 5000 characters)

The automatic detection of critical transitions is an open problem in complex systems (Scheffer et al., 2012), and has several fallouts in diverse application fields. For instance, in ecosystems there can be abrupt onset of desertification or sudden extinction of species (Scheffer et al, 2001), medical conditions can quickly change, as in asthma or epilepsy (McSharry et al., 2003), financial markets can transition to instability and crisis (May et al., 2008), and climate and its constituents can abruptly change (Alley et al., 2003). Ideally, one would either use data-driven (model-free) approaches, or obtain a fully calibrated model of the network system under analysis. Unfortunately, both methods are seldom viable when studying complex systems, since they would require qualitatively rich datasets. In applications, instead, our ability to detect, classify, and predict the emergence of critical transitions and tipping points is often hindered by the limitations on the available data. Specifically, the time series we are able to collect are affected by noise, and characterized by limited spatial and temporal resolution. For instance, in contemporary psychopathology, the onset of mental illness is viewed as an undesired equilibrium point in a dynamical network of symptoms. When analyzing longitudinal data collected on patients' mental health, we must cope with the tradeoff between the time-resolution of the data and the willingness and compliance of the patients in reporting answers on their mental health.

In this project, we will cope with this data limitations by developing methods to detect the salient causal relations in network dynamical systems, and evaluate their vulnerability (De Lellis and Porfiri, 2021), so as to identify in real-time possible tipping points towards undesired configurations. In the context of psychopathology, we will then design a mathematically principled integrated model of persons with mental illness capable of i) pinpointing the causal relationships across symptoms of mental disorders, and ii) determining how these symptoms are triggered or mitigated by socio-environmental factors. Toward this goal, we will embrace the complex system approach to mental disorders, which stems from a bulk of empirical and methodological research in psychopathology that investigates mental disorders as networks of interacting symptoms (Borsboom et al., 2017). Namely, pathological mental states are not caused by an underlying disorder, but the symptoms themselves and their causal relationships constitute the mental disorder. Using tools from dynamical systems theory and causal inference in statistics and information theory, we will describe each individual as a network of potential symptoms, with each node described as a bistable system, whose equilibria correspond to the absence or manifestation of a given symptom, respectively. Data-driven information theoretic methods, such as transfer entropy (Porfiri and Ruiz Marin, 2019; De Lellis et al., 2022) will be used to infer the causal links between the symptoms. The model will be validated and tuned on the multifaceted dataset collected through the cooperation with the ASL (Local Health Unit) Roma 2.

The objective of this doctoral project is to push forward the promising results on causal discoveries and early warning in network systems, and lead to the automation of the detection of critical transitions, enhancing our ability to analyze and predict the behavior of complex systems under limitations on the available data. Our theoretical findings will be experimentally validated on longitudinal data collected on mental health patients in the supported houses supervised by the Local Health Authorities in Rome. The outcome of the project may result in an improved ability to early detect transition in the mental health state of a patients, early enough for the psychopathologist to act and adjust its therapeutical plan.

This project brings forward a transformative, interdisciplinary approach across complex systems, information theory, dynamical systems theory, and psychopathology, which promises a breakthrough in the automatic detection and prediction of emerging behaviors and tipping points. The project validation will be based on real data gathered in the Local Health Unit in Rome, under the supervision of prof. Caroppo. The same premises will be used for validating the algorithms for early warning that will be developed within the project.

Relevance to the MERC PhD Program (max 2000 characters)

This projects ideally fits the spirit of the MERC PhD program, with respect to its criteria of excellence, interdisciplinary nature, and transformative potential. The team of advisors involves experts from three different countries (US, Spain, and Italy) with a proven record of collaboration and mentorship of doctoral students. The expertise of the team spans from highly theoretical dynamical systems to data-driven methods to psychiatry and psychopathology. The mathematical and statistical tools upon which the project is based are at the frontier of knowledge in complex systems, thereby offering an invaluable learning basis for students and an empowering opportunity to contribute to the state of knowledge. Dynamical systems, machine learning, network science, time-series analysis have a central role in the proposal, all topics that ideally fit with the training and curricula of the PhD program. The students will be guided through the challenges of interdisciplinary research, learning how to cope with the different languages and tools used across the disciplines. Beyond enriching their skills in fundamental science, the project will also offer opportunity for students to apply their knowledge on a specific application, with potential impact for early diagnosis of critical transition in psychopathologies. Also, the algorithm that the students will develop during the project will be validated on data collected at the Local Health Unit in Rome.

Key references

- Scheffer, M., et al. (2012). Anticipating critical transitions. *Science*, *338*(6105), 344–348.
- Scheffer M., Carpenter S., Foley J.A., Folke C., Walker B. (2001). Catastrophic shifts in ecosystems, *Nature* 413, 591–596.
- McSharry P.E., Smith L.A., Tarassenko L., (2001). Prediction of epileptic seizures, *Nature Medicine* 9 (2003) 241–242.
- May R., Levin S.A., Sugihara G. (2008). Ecology for bankers, *Nature* 451, 893–895.
- Alley R.B., et al. (2003). Abrupt climate change, *Science* 299, 2005–2010.
- De Lellis, P., & Porfiri, M. (2021). Detection of influential nodes in network dynamical systems from time series. IEEE Transactions on Control of Network Systems, 8(3), 1249-1260.
- Borsboom, D. (2017). A network theory of mental disorders. *World Psychiatry*, 16(1), 5-13.
-Porfiri, M. and Ruiz Marín, M. (2019). Transfer entropy on symbolic recurrences. Chaos 29, 063123.
- De Lellis, P., Ruiz Marín, M. & Porfiri M., (2022). Inferring directional interactions in collective dynamics: a critique to intrinsic mutual information, *Journal of Physics: Complexity*, Focus Issue: Monitoring and Control of Complex Supply Systems, 4(1), 015001.

Joint supervision arrangements

The supervisors are close friends who are excited about the project and discuss science on a regular basis, multiple times per week. As such, students will be part of a vibrant team, where discussions continuously happen in an organic and natural manner. Hence, the frequency of meetings will depend on the stage of the research carried out by the student and on the very need they will have. We expect that there will be periods when meeting twice per month with the all group will be

sufficient, for instance, when the student is learning and studying some methodology or the state of the art, and other periods when one-on-one meetings with any of the supervisors should happen two or three times per week, for example, when dealing with the development of new models or algorithms. For the mathematical, statistical, and modeling aspect of the project, Professors Porfiri, Ruiz, and De Lellis will take the heaviest lift in mentoring the student. When dealing with specific aspect of the psychopathological part of the project, Dr. Caroppo will be the key supervisor.

Location and length of the study period abroad (min 12 months)

The New York University (NYU) Tandon School of Engineering is the engineering and applied sciences school of NYU. Tandon is the second oldest private engineering and technology school in the United States. Located in the Brooklyn Tech Triangle, ten minutes walking to the Brooklyn Bridge and connected with subway or NYU to any of the other NYU schools in the City. Prof. Porfiri is an Institute Professor (the highest distinction at NYU Tandon), with tenured appointments in Biomedical Engineering and Mechanical and Aerospace Engineering. Prof. Porfiri's laboratory, the Dynamical Systems Laboratory (DSL), was founded fifteen years ago with the vision of creating an interdisciplinary space with fundamental research in dynamical systems with clear societal impact. The laboratory is housed between the Center for Urban Science and Progress (CUSP) and the Department of Mechanical Engineering. MERC students joining the project will have office space in the newly renovated CUSP building and access to any of the DSL facilities. At the DSL, they will be fully integrated in any of the lab activities, such as seminars, workshops, focused courses for professional developments, and collaborative efforts within and outside the group.

Technical University of Cartagena (UPCT) offers several different study programs across engineering, economics, and business sciences. The historical city of Cartagena belongs to the autonomous province of Murcia. Cartagena is located in the southeast of Spain, right at the Mediterranean Sea. The combination of tradition and modernity gives UPCT a vibrant, adventurous and innovative character. Prof. Ruiz is the principal investigator of the excellence research group Economic Modelling and Non-Parametric Statistic (EMODs), an interdisciplinary research group specialized in the analysis and applications of nonlinear time series, complex networks and spatial processes. MERC students joining the project will have office space and access to any of the UPCT facilities.

Ideally, we would like the student to spend 18 to 24 months abroad to ensure ample opportunities for training and full integration with the supervisors' research teams. How to split the time between US and Spain will be discussed based on student preferences; we also anticipate that, under normal circumstances, Prof. Porfiri visits UPTC regularly and so does Prof. Ruiz visits NYU.

Any other useful information

Prof. Porfiri is also a faculty member of the Department of Biomedical Engineering, bringing along access to a number of related learning opportunities in health-related research. For example, he is one of the key investigators of two National Science Foundation Projects on telehealth, machine learning, and rehabilitation between Tandon, the School of Medicine, and the private sector (Facebook and Microsoft). MERC students will be welcome to be involved in these activities, participate in related meetings, and attend lectures and seminars.

The ASL Roma 2 is the Local Health Authority that takes care of the health needs of the citizens living in a part of the city of Rome, which includes the Municipalities IV, V, VI, VII, VIII and IX. The

ASL Roma 2 has three directly managed hospitals: the Sandro Pertini Hospital, the Sant'Eugenio / CTO Andrea Alesini Hospital and the Community and Operational Center Hospital. The ASL Roma 2 is configured as an organization that acts for the improvement of the health status of the citizens, with specialized units focused on the prevention, treatment, and follow-up of mental health issues.