# Controlling Complex Networks: When Control Theory Meets Network Science

*Satellite symposium of NetSci2019, Burlington, Vermont, USA*

**Date: May 28, 2019**

**Venne**: Aiken Hall (room 102), University of Vermont

**Registration** of this symposium is free of charge. Yet, symposium participants still need to register for the NetSci main conference.

**Organizers:**
Yang-Yu Liu
Marco Tulio Angulo

SYMPOSIUM

# CONTROLLING COMPLEX NETWORKS

## from Biological to Social and Technological Systems

May 28, 2019
Burlington, Vermont

**Speakers (in alphabetic order):**

**Andrea Aparicio**
**Atsushi Mochizuki**
**Fabio Pasqualetti**
**Guoping Jiang**
**Mariana Gómez-Schiavon**
**Ophelia Venturelli**
**Peter Caines**
**Yoed N. Kenett**
**Yize Chen**
**Yizhou Sun**

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NetSci

NetSci Satellite Symposium – ***Controlling Complex Networks***
May 28, 2019
**Program**

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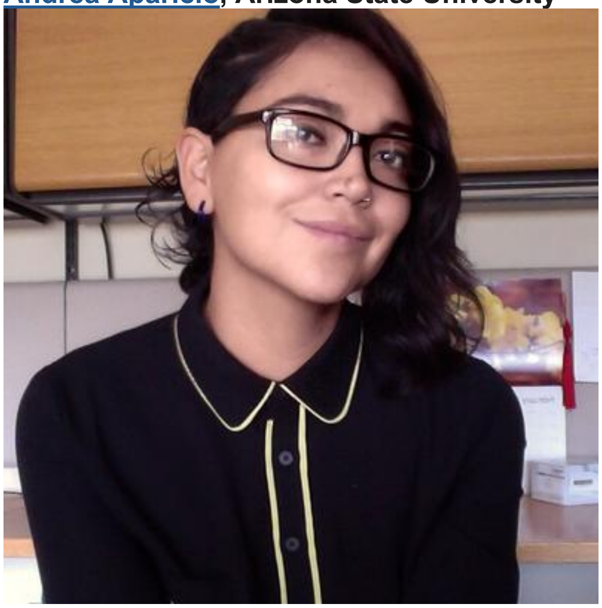
|---|---|
| 8:30-8:35 | Sign in |
| 8:35-8:40 | **Welcome address (Yang-Yu Liu)** |
| | **Session I (Chair: Marco Tulio Angulo)** |
| 8:40-9:20 | **Ophelia Venturelli**: *Predicting the structure and butyrate production of synthetic human gut microbiome communities* |
| 9:20-10:00 | **Andrea Aparicio**: *Identifying sensor species to predict critical transitions in complex ecosystems* |
| 10:00-10:15 | Break |
| | **Session II (Chair: Yize Chen)** |
| 10:15-10:55 | **Atsushi Mochizuki**: *Controlling cell fate specification system based on network structure* |
| 10:55-11:35 | **Mariana Gómez-Schiavon**: *Design and analysis of a Proportional-Integral-Derivative controller with biological molecules* |
| 11:35-12:15 | **Yizhou Sun:** *Understanding the Co-Evolution of Opinion Migration and Network Evolution* |
| 12:15-1:45 | Lunch |
| | **Session III (Chair: Yang-Yu Liu)** |
| 1:45-2:25 | **Peter Caines**: *Graphon Linear Quadratic Regulation and Graphon Mean Field Games for Large Scale Networks* |
| 2:25-3:05 | **Fabio Pasqualetti**: *Controllability Metrics, Limitations and Algorithms for Complex Networks* |
| 3:05-3:25 | Break |
| | **Session IV (Chair: Andrea Aparicio)** |
| 3:25-4:05 | **Xinwei Wang**: *Synchronization and Controllability of Complex Dynamical Networks* |
| 4:05-4:45 | **Yoed N. Kenett**: *Investigating Creativity from a Controllability Perspective* |
| 4:45-5:25 | **Yize Chen**: *Optimal Control via Neural Networks* |
| 5:25-5:30 | **Conclusion (Marco Tulio Angulo)** |

# Abstracts

**Andrea Aparicio, Arizona State University**

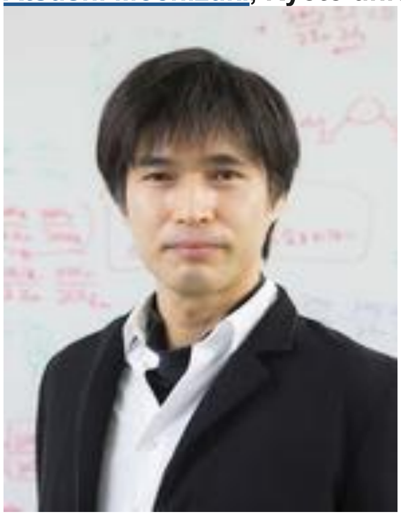


**Identifying sensor species to predict critical transitions in complex ecosystems**

**Abstract**: Monitoring ecosystems can help to predict sudden changes in their state, and enforce that they keep providing the necessary services that they produce. However, when these ecosystem have a large number of species the monitoring can become challenging because it might be infeasible to measure the activity of all of them. To overcome this challenge we created a method to identify minimal sets of species that render the ecosystem observable requiring only the structure of their associated network, and not their specific dynamics. These sets of minimal species can be used to identify early-warning signals of critical transitions in the ecosystems' state.

**Bio**: Andrea Aparicio is a postdoctoral associate in the School of Mathematics and Natural Sciences of Arizona State University. Her main research interests include control theory, observability, robust control, and biological control applications. This last is her current research topic.

Atsushi Mochizuki, Kyoto university, Japan



**Controlling cell fate specification system based on network structure**

**Abstract:** By the success of modern biology we have many examples of large networks which describe regulatory interactions between a large number of genes. On the other hand, we have a limited understanding for the dynamics of molecular activity based on such complex networks. To overcome these problems, we developed Linkage Logic theory to analyze the dynamics of complex systems based on information of the regulatory linkages alone. It assures that i) any long-term dynamical behavior of the whole system can be identified/controlled by a subset of molecules in the network, and that ii) the subset is determined from the regulatory linkage alone as a feedback vertex set (FVS) of the network. We applied this theory to the gene regulatory network for cell differentiation of ascidian embryo, which includes more than 90 genes. From the analysis, dynamical attractors possibly generated by the network should be identified/controlled by only 5 genes, if the information of the network structure is correct. We verified our prediction by combinatorial experiments of knockdown and overexpression by using ascidian embryos. We found that almost all of the expected cell types, six among seven major tissues, could be induced by experimental manipulations of these five genes.

**Bio:** Atsushi Mochizuki was born in Shizuoka, Japan, in 1969. He graduated from the Faculty of Sciences, Kyoto University, in 1994, and obtained his PhD in 1999 from Kyushu University. He was promoted to assistant professor in 1998 at Kyushu University, to associate professor in 2002 at National Institute for Basic Biology, to chief scientist in 2008, and to professor in 2018 at Kyoto University. His researches focus on the mathematical and computational studies on biological phenomena in molecular and developmental biology. One of his largest achievements is to establish "Structural Theories for Network Systems", by which important aspects of dynamical properties of complex systems are determined from topologies of networks alone. He was awarded 11th JSPS PRIZE (2015) from Japan Society for the Promotion of Science.

Fabio Pasqualetti, University of California at Riverside

**Controllability Metrics, Limitations and Algorithms for Complex Networks**

**Abstract**: Real-world systems, including interconnected power, social, and cyber–physical systems, can often be represented as complex networks, and their dynamic behavior depends to a large extent upon the properties of their interconnection structure. Our ability to manipulate and reconfigure complex networks through local interventions is fundamental to guarantee reliable and efficient network functionalities. Typically, it is not feasible nor desirable to control each network component, thus the importance to identify optimal control components and strategies, and to characterize to what extent few control components can reprogram complex networks. In this talk I will present different metrics for network controllability, and I will highlight how the network structure and weights fundamentally limit our ability to control complex networks. In particular, I will show that most complex networks are difficult to control by few control nodes, as the control energy grows exponentially with the network cardinality. Conversely, I will characterize certain "anisotropic" networks whose controllability degree is independent of the network cardinality and thus easy to control. Additionally, I will show how controllability and robustness are competing objectives in complex networks, thus offering a first explanation as to why many natural, biological, and technological network systems are in fact difficult to control. Finally, I will discuss some possible research directions.

**Bio**: Fabio Pasqualetti is an Assistant Professor in the Department of Mechanical Engineering, University of California at Riverside.
He completed a Doctor of Philosophy degree in Mechanical Engineering at the University of California, Santa Barbara, in 2012, a Laurea Magistrale degree (M.Sc. equivalent) in Automation Engineering at the University of Pisa, Italy, in 2007, and a Laurea degree (B.Sc. equivalent) in Computer Engineering at the University of Pisa, Italy, in 2004. He has received several awards, including a Young Investigator Program award from ARO in 2017, and the 2016 TCNS Outstanding Paper Award from IEEE CSS. His main research interests include the analysis and control of complex networks, security of cyber-physical systems, and network neuroscience.

**Guoping Jiang, Nanjing University of Posts and Telecommunications, China**

**Synchronization and Controllability of Complex Dynamical Networks**

**Abstract**: In this talk, I will first introduce two different forms of node coupling in complex dynamical networks, including state coupling and output coupling, which are essential and common in the network models. Then, I will talk more about the synchronization for complex dynamical networks, focusing on inner and outer synchronization with different node coupling, and some applications in topology identification and fault diagnosis of complex dynamical networks. Finally, I will present some recent achievements of our group in the synchronization for the complex dynamical network using the output coupling network model, and some progress in the structural controllability of complex dynamical networks with multi-dimensional node dynamics.

**Bio**: Guo-Ping Jiang received the Ph.D. degree in control theory and engineering from Southeast University, Nanjing, China, in 1997. He is currently a Professor and the Vice President with the Nanjing University of Posts and Telecommunications, China, and is the Director of Jiangsu Engineering Lab for IOT Intelligent Robots. He is a Member of Technical Committee of IEEE Nonlinear Circuits and Systems. He has authored or coauthored over 200 published articles and 2 books in the area of nonlinear systems and control. His current research interests include synchronization and control of chaos and complex dynamical networks. Prof. Jiang was a recipient of the New Century Excellent Talents Award of the Ministry of Education, China, in 2006.

Mariana Gómez-Schiavon, University of California, San Francisco

**Design and analysis of a Proportional-Integral-Derivative controller with biological molecules**

**Abstract**: The ability of cells to regulate their function through feedback control is a fundamental underpinning of life. The capability to engineer de novo feedback control with biological molecules is ushering in an era of robust functionality for many applications in biotechnology and medicine. To fulfill their potential, feedback control strategies implemented with biological molecules need to be generalizable, modular and operationally predictable. Proportional-Integral-Derivative (PID) control fulfills this role for technological systems and is a commonly used strategy in engineering. Integral feedback control allows a system to return to an invariant steady-state value after step disturbances. Proportional and derivative feedback control used with integral control help sculpt the dynamics of the return to steady-state following perturbation. Recently, a biomolecular implementation of integral control was proposed based on an antithetic motif in which two molecules interact stoichiometrically to annihilate each other's function. In this work, we report how proportional and derivative implementations can be layered on top of this integral architecture to achieve a biochemical PID control design. We illustrate through computational and analytical treatments how the addition of proportional and derivative control can improve performance, and discuss practical biomolecular implementations of these control strategies.

**Bio**: I am a computational biologist who focuses on understanding the emergent properties of dynamic regulatory systems, in particular gene networks. Throughout my post-graduate education (CINVESTAV 2009-2011, Duke University 2011-2016) I studied the properties and evolutionary emergence of gene regulatory bistable switches. Currently I am a postdoctoral fellow in the El-Samad lab at UCSF, where I am exploring the principles and limitations of cellular feedback control.

**Ophelia Venturelli, University of Wisconsin-Madison**

**Predicting the structure and butyrate production of synthetic human gut microbiome communities**

**Abstract:** The human gut microbiota produces and degrades metabolites that are major drivers of human health and disease. Developing the capability to precisely control gut microbial metabolites could provide novel therapeutic strategies for multiple human diseases linked to gut microbial metabolic activities. By studying synthetic communities comprised of human-intestinal isolates, high-throughput methods can be used to explore the community design space to link metabolic activities to community context. We develop a predictive modeling approach using synthetic human gut microbiome communities to investigate how production of the bacterial short-chain fatty acid butyrate is shaped by microbial interactions. To this end, we characterized the growth and metabolite production of 25 highly prevalent and diverse species, 5 of whose genomes encode the butyrate metabolic pathway. We quantified the impact of pairwise interactions on butyrate production using high-throughput measurements of growth and metabolite concentrations. This initial dataset was used to parameterize a dynamic computational model using tools from machine learning to predict community structure and butyrate production. This model illuminates microbial interactions that have the largest impact on butyrate production and can be used to design multi-species consortia that exhibit high butyrate production. Our work provides key insights into the ecological forces influencing butyrate production in the human gut microbiome. Further, our methods can be used for the rational design of the structure and function of diverse microbial communities.

**Bio**: Dr. Ophelia Venturelli is an Assistant Professor in Biochemistry at UW-Madison. She began her appointment in July 2016 after completing a Life Sciences Research Foundation Fellowship at UC Berkeley in the laboratory of Dr. Adam P. Arkin. Dr. Venturelli's postdoctoral research focused on developing methods to decipher microbial interactions in synthetic human gut microbiome communities and strategies to manipulate intracellular resource allocation. She received her PhD in Biochemistry and Biophysics in 2013 from Caltech with Richard M. Murray, where she studied single-cell dynamics and the role of feedback loops in a metabolic gene regulatory network. The Venturelli lab focuses on understanding and engineering microbial communities using synthetic biology. Dr. Venturelli received the Shaw Scientist Award (2017), ARO Young Investigator Award (2017) and the NIH Outstanding Investigator Award (2017).

**Peter Caines, McGill University, Canada**

**Graphon Linear Quadratic Regulation and Graphon Mean Field Games for Large Scale Networks**

**Abstract:** To achieve control objectives for extremely complex and very large scale networks using standard methods is intractable. In this work we develop a methodology for the approximate control of systems distributed over arbitrarily large complex networks via the graphon limit theory of sequences of complex graphs together with the theory of infinite dimensional linear control systems. Approximation schemes applied to the optimal infinite system control laws yield feedback laws which are utilized on the original large-scale finite network system. A theory of convergence establishes the efficacy of this formulation. Numerical examples of complex networks with randomly sampled weightings illustrate the use of the methodology. Furthermore, decentralized control of networks of agents each of which is associated with a stochastic dynamical system is being formulated in terms of a theory of Graphon Mean Field Games (GMFG) in which asymptotically infinite populations of non-cooperative agents distributed over an unbounded network come into a Nash equilibrium by use of feedback control laws derived from the GMFG equations. (Work with Shuang Gao and Minyi Huang.)

**Bio:** Peter E. Caines received the BA in mathematics from Oxford University in 1967 and the PhD in systems and control theory in 1970 from Imperial College, University of London, supervised by David Q. Mayne, FRS. In 1980, he joined McGill University, Montreal, where he is James McGill Professor and Macdonald Chair in the Department of Electrical and Computer Engineering. In 2000, his paper on adaptive control with G. C. Goodwin and P. J. Ramadge (IEEE TAC, 1980) was recognized by the IEEE Control Systems Society as one of the 25 seminal control theory papers of the 20th century. He received the IEEE Control Systems Society Bode Lecture Prize in 2013, is a Fellow of CIFAR, SIAM, IEEE, the IMA (UK) and the Royal Society of Canada (2003), and is a member of Professional Engineers Ontario. Peter Caines is the author of Linear Stochastic Systems (Wiley,1988, republished as a SIAM Classic in 2018. His research interests include stochastic, mean field game and hybrid systems theory together with their applications to natural and artificial systems.

**Yoed N. Kenett, University of Pennsylvania**

**Investigating Creativity from a Controllability Perspective**

**Abstract:** The creative process is mostly considered as a two-stage process – generation of novel ideas, and evaluation of the ppropriateness of these ideas. Different theories have been proposed to account for this two-stage dynamic process that attribute significance to the role of cognitive control in the creative process. However, the neurocognitive underpinnings of these two stages are far from understood. In this talk, I will present my work applying network control theory on brain structural connectivity networks to investigate controllability of different brain regions in the creative process. This work highlights how network control theory can be applied to shed novel light on high-level cognitive processes, such as creativity and intelligence.

**Bio:** Yoed Kenett has a Ph.D. (2015) in neuroscience from Bar-Ilan University, Israel. Currently he is a postdoctoral fellow at the Department of Psychology at the University of Pennsylvania, working at the labs of Dr. Sharon Thompson-Schill and Dr. Anjan Chatterjee. His research computationally and empirically investigates the structure of semantic memory (our memory of knowledge and facts) and how it constrains cognitive processes operating over it, such as creativity, memory retrieval and aesthetics, in typical and clinical populations.

Yize Chen, University of Washington

**Optimal Control via Neural Networks**

**Abstract**: Control of complex systems involves both system identification and controller design. Deep neural networks have proven to be successful in many identification tasks, however, from model-based control perspective, these learned deep networks are difficult to work with, because they are typically nonlinear and nonconvex. Therefore many systems are still identified and controlled based on simple linear models despite their poor representation capability. In this talk, we investigate how to bridge the gap between model accuracy and control tractability with the involvement of deep learning models. By explicitly constructing neural networks that are convex with respect to their inputs, we show that they can be trained to obtain accurate models of complex physical systems. In particular, we design input convex recurrent neural networks to capture temporal behavior of dynamical systems. Then optimal controllers can be designed via solving a convex model predictive control problem. Experiment results demonstrate potentials of the proposed input convex neural network based approach in a variety of control applications. In particular, we show that in the MuJoCo Robotic locomotion tasks, we could achieve over 10% higher performance using 5× less time compared with state-of-the-art model-based reinforcement learning method; and in the building HVAC control example, our method achieved up to 20% energy reduction compared with classic linear models.

**Bio:** Yize Chen works in the area of optimization, machine learning and control. He is interested in the decision-making under complex environments, and understanding the decisions made by data-driven methods, and the major focus has been on cyber-physical systems and biological systems. He received his Bachelor degree in Control Science in 2016 at Zhejiang University, and he is currently pursuing his PhD degree in Electrical and Computer Engineering at University of Washington. He was a visiting student(2016) at Harvard Medical School and research intern(2018) at Los Alamos National Laboratory.

**Yizhou Sun, University of California, Los Angeles**

**Understanding the Co-Evolution of Opinion Migration and Network Evolution**

**Abstract**: Nowadays social media, such as Twitter and all kinds of online forums, becomes a platform where people can express their opinions implicitly or explicitly. For example, in Twitter, people follow people they trust, and retweet the tweets they agree. In online forums, such as PoliticalForum.com, people explicitly express their opinions and interact with each other using text. Our goal is to understand people's stance on some (political) issue according to their online behaviors that can be captured in social media, including links they have issued and content they have generated, which is essential for national security and policy making. Existing attempts in this direction, however, oversimplified the problem in several aspects. First, they usually treat the user stance prediction problem as a binary classification problem and ignore their relative polarity. Second, most of the methods do not attempt to understand the rationality behind their online behaviors. Third, these methods usually treat networks as static and do not model the dynamics of the complex system. In contrast, we attempt to overcome these challenges. In particular, three specific user stance prediction problems will be included in this talk: (1) political ideology detection for ordinary twitter users via their heterogeneous types of links; (2) user stance prediction in news commenting system and online forums via combined link and text analysis. and (3) a co-evolution model that explains the dynamics of opinion migration and network evolution. These methodologies may benefit more applications ranging across a wide spectrum of domains.

**Bio**: Yizhou Sun is an associate professor at department of computer science of UCLA. Prior to that, she was an assistant professor in the College of Computer and Information Science of Northeastern University. She received her Ph.D. in Computer Science from the University of Illinois at Urbana-Champaign in 2012. Her principal research interest is on mining graphs/networks, and more generally in data mining, machine learning, and network science, with a focus on modeling novel problems and proposing scalable algorithms for large-scale, real-world applications. She is a pioneer researcher in mining heterogeneous information network, with a recent focus on deep learning on graphs/networks. Yizhou has over 90 publications in books, journals, and major conferences. Tutorials of her research have been given in many premier conferences. She received 2012 ACM SIGKDD Best Student Paper Award, 2013 ACM SIGKDD Doctoral Dissertation Award, 2013 Yahoo ACE (Academic Career Enhancement) Award, 2015 NSF CAREER Award, 2016 CS@ILLINOIS Distinguished Educator Award, and 2018 Amazon Research Award.