

COMPLEX NETWORKS & SYSTEMS IN THE PHD PROGRAM IN INFORMATICS

TRACK DIRECTOR: LUIS M. ROCHA

SUMMARY

The Complex Networks & Systems track, with its unique interdisciplinary values, offers a training opportunity to explore the connections among theoretical, technological, biological, and social implications of complex systems in a diverse and multidisciplinary research-oriented curriculum. The study of complex systems is focused on discovering and understanding how the myriad parts of a system—which could be the Internet, the human brain, a language, a power grid, or an ecosystem—interact with each other and determine the macroscopic behavior of the system itself. This strongly interdisciplinary field has exciting implications for computer science, physics, math, biology, and cognitive and social sciences. Faculty at the associated **Center for Complex Networks and Systems Research** (CNetS: <http://cnets.indiana.edu/>) are investigating complex systems in action, from determining how a particular YouTube video suddenly goes viral to developing models that can accurately predict the spread of contagious diseases.

The program also capitalizes on the new **Indiana University Network Science Institute** (IUNI: <http://iuni.iu.edu>) with over 150 faculty members who participate in network science and complex systems research and who can serve in interdisciplinary Ph.D. advisory committees. Indeed, the breadth and strength of research in network science and complex systems already pursued at Indiana University is unmatched by other academic programs. Our students come from around the world and have a variety of educational backgrounds. What they share is a desire to widen their theoretical, computational, and technical skills—and, from the earliest days of the program, to engage in research projects ranging from Web mining to modeling biochemical regulation. Our students have graduated to join some of the best academic, government and research and development centers in the World, ranging from top universities to the most advanced technology companies.

PRIMARY TRACK FACULTY

Yong-Yeol Ahn: Structure and dynamics of complex systems, such as society and living organisms, using massive datasets. Hierarchical & modular structure in social and biological networks, the analysis of metabolic networks, and the social media.

Randall Beer: Cognitive science, computational and theoretical biology. Understanding how coordinated behavior arises from the dynamical interaction of an animal's nervous system, its body and its environment. Evolution and analysis of dynamical "nervous systems" for model agents, neuromechanical modeling of animals, biologically-inspired robotics, and dynamical systems approaches to behavior and cognition.

Johan Bollen: Computational social science, social media analytics, informetrics, and digital libraries. Meme diffusion, markets and sentiment, metrics from usage data, science of science.

David Crandall: computer vision, visual object recognition and scene understanding, analyzing and modeling large amounts of uncertain data, notably in mining data from the web and from online social networking sites.

Simon DeDeo: Computation and cognition in large-scale biological and social systems, human cognition, biological computation, animal behavior and digital humanities.

Santo Fortunato: Statistical physics of social dynamics, Community structure in complex networks, Science of Science.

Alessandro Flammini: Information and Transportation Networks. City settlement activity, Information Creation and Consumption, Online Traffic, Protein Interaction Networks.

Filippo Menczer: Web science, social media, social networks, social computing, Web search and data mining, distributed and intelligent Web applications, and modeling of complex information networks.

Filippo Radicchi: Complex Networks and Systems, Data Science, Science of Science, Sport Analytics.

Luis Rocha: complex systems, computational biology, artificial life, embodied cognition and bio-inspired computing, dynamics in complex networks, text and literature mining, evolutionary systems, adaptive search and recommendation, and biosemiotics.

Peter Todd: Simple heuristics for decision making, structure of information in environments, evolution of behavior, information foraging, emergence of environment structure through interactions of populations of agents following simple behavioral rules, artificial life approaches to music, making decisions about food and eating, and cognition of consumption.

REQUIRED COURSES

All required courses provided by faculty in complex systems tracks, including I609 and I709, are open to and welcome students from other tracks and programs.

I601 – INTRODUCTION TO COMPLEX SYSTEMS

Note: This course is waived if students demonstrate familiarity with complex systems (e.g. M.S. in related field). It is taught every two years to guarantee sufficient quorum. It alternates with I585 (<http://www.informatics.indiana.edu/rocha/i-bic>) which students can take instead of I601.

Most Recent offering: <http://homes.soic.indiana.edu/classes/fall2013/info/i601-filiradi/advertisement.pdf>

MOTIVATION

Nature is complex. Biological, social, economic, technological and information systems are all composed of many interacting agents giving rise to macroscopic complex features. Complexity science is the novel interdisciplinary research field devoted to the understanding of the roots of complex phenomenology observable in nature, and to developing a common theoretical framework able to explain the astonishing similarity between complex real systems of so different origin.

AIMS

This course aims at providing an introduction to complex systems and networks. The course will touch several topics of traditional and current research in complexity science. Students will learn mathematical and statistical concepts of the science of complexity, and, by being exposed to a great deal of real examples, they will learn how to measure and characterize complex features in natural systems. These notions and analytic tools are increasingly in demand to approach complex problems in many different disciplines including biology, data and sport analytics, social science, informatics, neuroscience, and economics.

I609 – COMPLEX SYSTEMS ADVANCED SEMINAR I

This course is taught once every two years alternating with I709, to obtain a sufficient quorum of students. Majority of students from Complex Systems track, but students from other tracks and programs frequently take this seminar.

Most Recent offering: <http://www.informatics.indiana.edu/rocha/icx1/>

MOTIVATION

A complex system is any system featuring a large number of interacting components (agents, processes, etc.) whose aggregate activity is nonlinear (not derivable from the summations of the activity of individual components) and typically exhibits hierarchical self-organization under

selective pressures. This definition applies to systems from a wide array of scientific disciplines. Indeed, the sciences of complexity are necessarily based on interdisciplinary research. Almost all interesting processes in nature are highly cross linked. In many systems, however, we can distinguish a set of fundamental building blocks, which interact nonlinearly to form compound structures or functions with an identity that requires more explanatory devices than those used to explain the building blocks. This process of emergence of the need for new, complementary, modes of description is known as hierarchical self-organization, and systems that observe this characteristic are defined as complex. Examples of these systems are gene networks that direct developmental processes, immune networks that preserve the identity of organisms, social insect colonies, neural networks in the brain that produce intelligence and consciousness, ecological networks, social networks comprised of transportation, utilities, and telecommunication systems, as well as economies. The field of complex systems studies the general characteristics of all these systems. Its goal is to identify and model the laws and behaviors common to various classes of complex systems.

AIMS

This seminar is designed to present and discuss the history, methodology and impact of complex systems; we cover key literature as well as recent advances in the field.

EVALUATION

Students are expected to read and annotate the materials presented, as well as present several of the key readings. Students will also work on a term paper.

SYLLABUS

1. Part I: History of the Field
 - a. Cybernetics and the Informational Turn
 - b. Systems Science, Prediction, and Limits
 - c. Self-Organizing Systems
 - d. Second-Order Cybernetics
 - e. Organization of Complex Systems
2. Part II: Current Research
 - a. Towards a practice of Complex Systems
 - b. Evolutionary Systems
 - c. Information and Complexity
 - d. Neo-Cybernetics themes

READINGS FROM SPRING 2014

Listed at: <http://www.informatics.indiana.edu/rocha/icx1/index.html#materials>

I709 – COMPLEX SYSTEMS ADVANCED SEMINAR II

This course is taught once every two years alternating with I609, to obtain a sufficient quorum of students. Majority of students from Complex Systems track, but students from other tracks and programs frequently take this seminar.

Most Recent offering: <http://yongyeol.com/courses/2013S-I709/>

MOTIVATION

Complex systems are the systems that contain many sub-parts that interact with each other. Thanks to the structure and dynamics of interactions, fascinating and unpredictable phenomena emerge. Many natural and artificial systems that fascinate us (e.g. cells, brains, societies) are complex systems. Because complex systems exist all over the places, the study of complex systems is inherently interdisciplinary. In this course, we will try to find the answers to the following questions: What are the complex systems around us? What characterizes the complex systems approach? What are the fundamentals of complex systems approach? How has it been applied to other fields? What are the frontiers of the research? We will explore fascinating papers ranging from the fundamental theory to the various applications, along with individual research project.

AIMS

- To be able to think like a complex systems researcher.
- To be able to apply complex systems approaches to your research.
- To finish a small research project about complex systems.

EVALUATION

Paper Review (20%): a short review of the papers is due by the midnight before the class

Paper Presentation: Assigned moderators make a brief (~ 5 minutes) presentation about the premises and the results of the paper.

Project proposal: A two to four page document that contains project title, motivation, relevant prior work, approach, plan, proposal presentation.

Proposal Presentation: 20 slides, 1–5 presentation.

Progress report: draft of the final paper, with preliminary results.

Final project paper (40%): full research paper (~10 pages) with all the details.

Final presentation (20%): 10 minute presentation.

Participation (20%)

SYLLABUS

1. Schooling Flocks and Crowds
2. Traffic and Panic
3. Collective Behavior and Social Segregation
4. Emergence of Network Communities
5. Threshold Model and Information Diffusion
6. Social Contagion and Virality
7. Economic Complexity
8. Networks of Genes, Proteins, Diseases, and Drugs
9. Evolution: Cost Optimization in Brain
10. Evolution of Cooperation
11. $1/f$ Noise and Music
12. Fractal
13. Self-Organized Criticality
14. Power-Law
15. Common Patterns of Nature
16. Allometric Scaling
17. Cities
18. Boolean Networks
19. Robustness of Regulatory Networks
20. Control
21. Homophily and Influence
22. Laws of Mobility
23. Virtual Worlds
24. Stochastic Resonance
25. Data

READINGS FROM SPRING 2013

Listed at: <http://yongyeol.com/courses/2013S-I709/#schedule>

I690 MATHEMATICAL METHODS FOR COMPLEX SYSTEMS

Note: This course is waived if students demonstrate sufficient mathematical prior training (e.g. M.S. in related field). It is taught every two years to guarantee sufficient quorum.

Most Recent offering: <https://sites.google.com/site/aflammin/teachin/i690>

MOTIVATION

Complexity deals with the structural, behavioral, and organizational properties that emerge from the unsupervised local interactions of a multitude of elementary units. During this courses we will study the mathematical and computational techniques that have been developed to describe

and understand such properties. In doing so we will always discuss the math/algorithmic side in the context of specific examples; We will touch upon a number of important and fascinating sub-areas: linearity and non-linearity, chaos, self-similarity, stochastic processes, self-organization and network theory.

AIMS

To provide students with a technical (mathematical, computational) background to describe, model and reason in quantitative terms about Complex Systems.

EVALUATION

Students are required to simulate a number of "model-system". Some (minimal) programming skills are therefore required. Some college-level background in calculus, probability and linear algebra is also required. If these requirements are not met, a preliminary conversation with the instructor is appreciated.

SYLLABUS

Part 0: The Art of Modeling

- The role of abstraction
- Deterministic vs Random
- Microscopic vs Macroscopic
- Order and Disorder

Part 1.A: Deterministic systems with few degrees of freedom

Continuous dynamical systems

- Linearization and stability
- Phase space and qualitative analysis
- Elements of bifurcation theory

The role of non-linearity

- Recurrence equations
- Bifurcation, period doubling – the case of the logistic map
- Routes to chaos
- Universality and the renormalization group

Part 1B: Randomness - the basic

- Poisson process
- Random walks
- Multiplicative processes
- Branching processes
- Markov processes

Part 2: From microscopic to macroscopic

- From random walk to the diffusion equation
- From Langevin to Fokker-Plank equation

Collective Phenomena

- Cellular Automata.
- Mean field techniques, their limits and extensions.

- Precursor of organization: emergence of long-range interactions in space and time.
- Self-Organized Criticality.
- The emergence of structure and order.
- Information and Entropy.
- Beyond Gaussian statistics – power laws, their significance and possible causes.

Networks

- Small-world and scale-free networks.
- Generative models.
- Processes on “non-uniform” networks (e.g. traffic, epidemics, search, failures).

READINGS

1. N. Boccarda, *Modeling Complex Systems*, Springer-Verlag, NY (2004).
2. Y. Bar-Yam. *Dynamics of Complex Systems*. Westview Press, Boulder, CO (2003).
3. D. Sornette, *Critical Phenomena in Natural Sciences*. Springer-Verlag, Berlin, 2nd ed.(2003)
4. S. Boccaletti, V. Latora, Y. Morenod, M. Chavez and D.-U. Hwanga, *Complex networks: Structure and dynamics*, Physics Report, 424, 175-308 (2006)

OPTIONAL COURSES

In addition to required courses, faculty in the track offer courses that provide more targeted training in specific areas.

I585 – **Biologically-inspired computing** – Rocha: <http://informatics.indiana.edu/rocha/i-bic>

I590 - Topics in Informatics

Performance Analytics – Radicchi

Large-Scale Social Phenomena – DeDeo -

<http://homes.soic.indiana.edu/sdedeo/page11/page11.html>

Mining The Social Web – Ferrara - <http://www.emilio.ferrara.name/i400-590-mining-the-social-web/>

Data Visualization – Ahn - <http://yongyeol.com/courses/2013F-I400/>

Collective Intelligence – Bollen - <http://www.informatics.indiana.edu/jbollen/CI/>

Complex Networks & Their Apps – Ahn - <http://yongyeol.com/courses/2014S-I590/>

CSCI-B 657 - **Computer Vision** - Crandall

COGS-Q 580 - **Introduction To Dynamical Systems In Cognitive Science** – Beer - <http://mypage.iu.edu/~rdbeer/COGS-Q580/>

QUALIFYING EXAM

Written and oral examinations decided by program committee based on bibliography from 1609, 1709 and specific research interests of candidate. Typical written exam: three papers or one-week take home exam.

TYPICAL MINORS

Cognitive Science, Statistics, Biophysics,

SAMPLE DISSERTATION TITLES

Abi-Haidar, Alaa	An Adaptive Document Classifier Inspired by T-cell Cross-regulation of the Immune System
Mourao, Marcio	Reconstructing the Mechanisms and the Dynamical Behavior Complex Biochemical Pathways
Conover, Michael	Digital Democracy: The Structure and Dynamics of Political Communication in a Large Scale Social Media Stream
Frey, Seth	Complex Collective Dynamics in Human Higher-Level Reasoning: A Study Over Multiple Methods
Kaur , Jasleen	Emergence of Innovation and Impact in Science
Kolchinsky, Artemy	Measuring Scales: Integration and Modularity in Complex Systems
Mao , Huina	Modeling Economic and Financial Behavior from Large-scale Datasets
Shuai, Xin	Modeling Scholarly Communications Across Heterogeneous Corpra
Simas, Tiago	Stochastic Models And Transitivity In Complex Networks
Wang, Zhiping	Biomedical Literature Mining For Pharmacokinetics Numerical Parameter Collection
Weng, Lilian	Information Diffusion on Online Social Networks

SOME METRICS FOR COMPLEX NETWORKS & SYSTEMS GRADUATES

