Complexity Science
Spring 2015

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The Complexity Course is a survey of techniques, applications, and implications of complexity science and complex systems. This course aims to be both an introduction for students from other fields, and a forum for continued discussion within the complexity community. Topics include systems dynamics, chaos, scaling, fat-tailed distributions, fractals, information theory, emergence, criticality, agent-based models, graph theory, and social networks.

Within each topic, we will focus on two complementary goals:

1. Building an intuition: Complexity is all around us, and complexity science is most useful when it can be easily applied to situations and research.
2. Modeling and analysis: Understanding complexity requires mathematical formalization and computational approaches, which are powerful and widely applicable.

Each week, we will have 4 hours of lecture. The first session each week will be an introduction to the contexts, intuition, and implications of a topic in complexity science, followed by student presentations and discussions of assigned readings. The second session will be a hands-on lab/lecture, where students learn to use computational techniques. Topics in the two lectures will build upon and support each other. Theory and mathematics will be used to delve deeper into the techniques and intuitions.

The goal of the paper discussions will be to collectively "reconstruct" the concepts developed in the papers: for each paper, one student presenter explains the models and what they teach us about the system under study, and another identifies potential problems and missed opportunities. Each participant will be responsible for playing one of these roles as a discussion leader two to three times throughout the semester. It is essential that everybody grapple with the readings ahead of the respective lecture session.

Applications will draw from climate science, ecology, conflict, historical physics, social theory, epidemiology, and governance.

The course will include 4 hours of tutorials in python, and tools for scientific work in python such as numpy and scipy. At the end of the semester, lab sessions will be partly used to help students workshop their work for their final projects.

The Course structure is summarized in the Table below, while the content of each session is detailed below. These topics are subject to change.

Week	Theory and Intuition	Computation and Mathematics
1	Introduction to Complexity	Introduction to Python
2	System Dynamics	Calibration and Verification
3	Non-linearity and Chaos	Statistical Identification of Chaos
4	Entropy and Long Tails	Computing Entropy and Properties
5	Self-Organized Criticality	Cellular Automata
6	Scaling and Networks	Graphs and Classes
7	Agent-Based Models	Agent-Based Experiments
8	Cross-Scales and Adaptive Management	Computational Exploration of Patterns
9	Evolution and Adaptation	Genetic Algorithms
10	Dynamics on Networks	Spreading Simulations
11	Dynamics of Networks	Network Applications
12	Guest Lecture	Projects Check-In
13	The Future of Complexity	Structure Estimation
14	Project Presentations	Project Presentations

In addition to readings and presentations, there are six lab assignments, and a final project. The lab assignments are as follows:

1. **Non-linearity and systems**: fitting models to non-Gaussian data.
2. **Differential equations and chaos**: characterizing the dynamics of iterative

maps.
3. **Cellular automata**: implementing the earthquake SOC model.
4. **Agent-based models**: extending a human-environment spatial model with multiple agents.
5. **Genetic evolution**: Communities and optimization through genetic algorithm
6. **Graphs and networks**: determining properties of real-world graphs.

Students choose their own final projects, either individually or as small groups. Each final project must apply techniques from the class to a context relevant to the student(s).

The grading breakdown is as follows:
- Labs: 50-60%
- Final Project: 25-35%
- Participation (including paper presentations): 15%

The 10% range for labs and projects is available for students who want to put more time into their final project, and who then would have about 1 lab less homework.
PhD students who take this course for credit will be required to complete additional sections in the lab assignments.

Schedule and Materials

Week 1: Introduction to complexity
What is complexity? What is complexity science? What is it not? How have disciplines embraced complexity? Discussions of endogeneity and regimes.

Readings:

Theory
- "The Meaning of General System Theory" in General System Theory by L. von Bertalanffy
- Methods and techniques of complex systems science: An overview, by Cosma Shalizi

Supplementary:
- Complexity, Economics, and Public Policy, by Durlauf, 2011 http://www.ssc.wisc.edu/econ/Durlauf/comppubpol12-11-11final.pdf
- Simple lessons from complexity by Goldenfeld, N. and Kadanoff, L., 1999
- Simplifying complexity: a review of complexity theory by Manson, S, 2000

- ...Ant Fugue in Godel, Escher, Bach by Douglas R. Hofstadter

Week 2: Systems Dynamics
How does systems' dynamics represent dynamics? What can we learn from an SD model (tipping points, leverage, typical "shape" of time series). System models as ODEs.

Readings:

Theory
- Meadows, D. 1999. Leverage Points: Places to Intervene in a System.
- Senge, P. The Art and Practice of the Learning Organization. Chapters 2, 4 and 8.

Applications
- Lane, D.C. and J.V. Rosenhead 2000. Looking in the Wrong Place for Healthcare Improvements: A System Dynamics Study of an Accident and Emergency Department, *The Journal of the Operational Research Society*, Vol. 51, No. 5.
- Naill, 1992. A system dynamics model for national energy planning.

Tools
- Tests for building confidence in system dynamics models by Forrester, J.W. and Senge, P.M., 1978

Supplementary
- Systems Dynamics and the lessons of 35 years, 1991. by Jay Forrester.
- Sterman, J. 2002. All models are wrong: reflections on becoming a systems scientist.

Week 3: Non-linearity and Chaos
Implications of non-linearity in dynamical systems: chaos (sensitivity to initial conditions, impossibility of precise predictions, what we can learn from the system nevertheless, statistically and topologically), bifurcations (importance of understanding dependence on parameters), thresholds between regimes. Implications for management of resilience.

Readings:

- Chapter 12, "Strange Attractors", In *Non-linear Dynamics* by S. Strogatz.

- Jackson et al. 2001. Historical Overfishing and the recent collapse of coastal ecosystems
- Pascual and Dunne Ecological Networks: Linking Structure to Dynamics in Food Webs
- Scheffer et al. 2009 Early-warning signals for critical transitions
- Sugihara, G. et al. 2012. Detecting Causality in Complex Ecosystems. *Science* 338, 496

Supplementary

- The dynamics of measles in sub-saharan Africa by Ferrari et al. 2008, Nature.
- Chapter 3, “Some System Concepts in Elementary Mathematical Consolidation”, in *General System Theory* by L. von Bertanlaffy
- Anderson, et al. 2008. Ecological Thresholds and Regime Shifts: Approaches to Identification, *Trends in Ecology and Evolution*, Vol 24 (1).
- Regime shifts, resilience, and biodiversity in ecosystem management by Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C., 2004 (recommend to ecologists)
- Early Warning of unknown nonlinear shifts, by Carpenter, Brock, Ecology 2012.
- Poverty Traps and Appalachia, Durlauf 2011.
- Resilience, adaptability and transformability in social-ecological systems by Walker, B., Holling, C., Carpenter, S. and Kinzig, A., 2004

Week 4: Entropy and Long-tails

What are stochastic processes? What kinds of distributions do we see? Examples of fat-tail distributions and where they appear.
The effects of fat-tails: e.g., measures of biological diversity have no defined variance, the problem with climate prediction. The consequences of non-ergodicity.
Techniques in modeling and estimating stochastic systems: monte-carlo, calibration on unstable surfaces (e.g., GA), markov chain, L1-norms, copulas, non-parametric models.
Entropy, maximum entropy, information in Markov chains, and information flow through cellular automata grids. Computational complexity, and unknowability.

Readings:

Theory

- Sequential Monte Carlo Methods for Dynamic Systems by Liu, Jun S and Chen, R, 2010
- Liebovitch, Larry and Daniela Scheurle, 2000. Two Lessons from Factals and Chaos, *Complexity*, Vol 5(4).

- The Nature of Computation - Introductory chapter
- On the rationale of Maximum Entropy Methods, by Jaynes, Proceedings of IEEE 1982
- Computation in Cellular Automata: A Selected Review, by Melanie Mitchell, 1996

Applications

- Gerard H. Roe and Marcia B. Baker, 2007. Why Is Climate Sensitivity So Unpredictable? *Science* 318(629).
- Ole Peters, 2011. "Menger 1934 revisited," Quantitative Finance Papers 1110.1578.
- Barabasi, Albert, 2005. The origin of bursts and heavy tails in human dynamics, *Nature,* Vol 435.
- Maximum Entropy and the state-variable approach to macroecology, by Harte, Zillio, Conlisk and Smith, in Ecology, 2008.

Supplementary

- Some background on why people in the empirical sciences may want to better understand the information-theoretic methods by Anderson, 2003 *http://aicanderson2.home.comcast.net/~aicanderson2/home.pdf*
- Think Stats, Allan Downey [exercises]

Week 5: Self-Organized Criticality

Self-organized criticality, phase transitions, power-laws, and their implications.

Readings:

Theory

- Chapter 1 of Ubiquity: Why Catastrophes Happen by M. Buchanan
- Through the looking glass of complexity: the dynamics of organizations as adaptive and evolving systems, by Morel and Ramanujam, 2010
- Chapter 1 of Scaling by Barenblatt
- Power-law distributions in empirical data, by Clauset, Shalizi, and Newman, 2009

Applications

- Criticality and disturbance in spatial ecological systems, by Pascual and Guichard, 2005
- Positive feedbacks promote power-law clustering of Kalahari vegetation by Scanlon, Todd M Caylor, K, Levin, S, Rodriguez-Iturbe, I, 2007

Week 6: Scaling and Networks
The nature of dimensionality, units, and dimensional analysis.
Where do fractals appear in nature, and why? Self-similar networks in nature. Topics in the mathematical theories surrounding fractals, and their usefulness for complex models.

Readings:

Theory
- Chapters 11 of Nonlinear Dynamics and Chaos by S. Strogatz: “Fractals”
- Chapter 8 of The Computational Beauty of Nature, by Flake, 1998
- Self-similarity of complex networks. Song et al 2005.

Applications
- River Networks as scale invariant phenomena: Section 3 of Dan Rothman’s Modeling Environmental Complexity Lecture Notes
- Chapter 3 of Fractals and Multifractals in Ecology and Aquatic Science, by Seuront, 2009
- Chapter 5 of Where medicine went wrong, by West, 2006
- Albert-László Barabási & Réka Albert (October 1999). "Emergence of scaling in random networks." *Science.* **286** (5439): 509–512.

Week 7: Agent Based Model
Consequences and metrics of spatial heterogeneity, proximity effects, local interactions to global effects, emergence. Path dependence, DNA and evolution and their computational analogs (genetic algorithms etc…). Turbulence and noise characteristics in space.

Readings:

- Axelrod, R. (1997). The dissemination of culture a model with local convergence and global polarization. *Journal of conflict resolution*, *41*(2), 203-226.
- Bryson, J. J., Ando, Y., & Lehmann, H. (2007). Agent-based modelling as scientific method: a case study analysing primate social behaviour.*Philosophical Transactions of the Royal Society B: Biological Sciences*,*362*(1485), 1685-1699.

Supplemental

Theory and Tools

- Practices for Computational Modeling (Appendix B of Complex Adaptive Systems by Miller and Page)
- The importance of being discrete (and spatial) by Durrett, R. and Levin, S., 1994
- Percolation: Section 6 of Dan Rothman's Modeling Environmental Complexity Lecture Notes

Applications

- Agent-based modelling as scientific method: a case study analysing primate social behaviour by Bryson, Joanna J. , Ando Yasushi and Hagen Lehmann
- Conquest and Regime Change: An Evolutionary Model of the Spread of Democracy and Peace by Cederman and Gleditsch.
- Global Pattern Formation and Ethnic/Cultural Violence. May Lim et al. (2007)

Week 8: Cross-scales and adaptive management

The problem of scales, hierarchy theory, and techniques for understanding cross-scale interactions and management. Scale separation versus self-similarity versus multiscale analysis.

Readings:

- Multiple Scales and the Maintenance of Biodiversity by Levin, Simon
- Panaceas and diversification of environmental policy by Brock and Carpenter

Applications (student presentation options):

- Accounting for uncertainty in ecological analysis: the strengths and limitations of hierarchical statistical modeling, Cressie et al (2009)
- Modeling Multilevel Data Structures, Steenbergen and Jones (2002)
- The Use of Discontinuities and Functional Groups to Assess Relative Resilience in Complex Systems, Allen, Gunderson and Johnson, 2005.
- The politics of scale, position, and place in the governance of water resources in the Mekong region, by Lebel, Garden, and Imamura, 2005

Supplementary

- Hierarchical Bayesian Modeling by Alan M. Zaslavsky
- The scale issue in social and natural sciences, by Danielle Marceau
- A hierarchical framework for the analysis of scale, O'Neill, Johnson and King.
- On time and space decomposition of complex structures, by P-J. Courtois
- Multiple scales and the maintenance of biodiversity, by Levin, 2000
- Multiscale Low-frequency circulation modes in the global atmosphere, by Lau et

al. 1994
- Resilience, Robustness, and Marine Ecosystem-based Management, by Levin and Lubchenko, Bioscience 2008.
- A Mathematical Theory of Strong Emergence Using Multiscale Variety, by Bar-Yam, Complexity 2004
- An introduction to hierarchical system theory, by Smith and Page, Computers and Electrical Engineering, 1973

Week 9: Evolution and Adaptation
What is evolution? How is it modeled? Continuous trait evolutionary dynamics. Drift as a null process. Evolution of whole systems, with application to technology systems. Evolvability.

Readings:

Theory
- Nowak 2006. Evolutionary Dynamics: Exploring the Equations of Life
- Kauffman 1993. The Origins of Order. Self-Organization and Selection in Evolution
- Holland, John H. "Genetic algorithms." *Scientific american* 267.1 (1992): 66-72.
- Herber Simon 2000 Near decomposability and the speed of evolution

Applications
- Nowak et al. 2004. Emergence of cooperation and evolutionary stability in finite populations. *Nature*
- Frenken, Nuvolari 2004. The early development of the steam engine: an evolutionary interpretation using complexity theory
- McNerney et al. 2011 Role of design complexity in technology improvement
- Kandler and Shennan 2013. Non-equilibrium neutral model for analysing cultural change

Week 10: Dynamics on Networks
The applicability of networks to representing social relationships. Information flow through social networks. Central players and the significance of network statistics for social behaviors.

Readings:

Theory

- Collective dynamics of 'small-world' networks by Watts, D J, Strogatz, S H, 1998
- Newman, Mark EJ. "The structure and function of complex networks." *SIAM review* 45.2 (2003): 167-256.

Applications

- Shalizi, Cosma Rohilla, and Andrew C. Thomas. "Homophily and contagion are generically confounded in observational social network studies." *Sociological Methods & Research* 40.2 (2011): 211-239.
- Distinguishing influence-based contagion from homophily-driven diffusion in dynamic networks. Aral et al 2009.
- Onnela, J-P., et al. "Structure and tie strengths in mobile communication networks." *Proceedings of the National Academy of Sciences* 104.18 (2007): 7332-7336.
- Macy, Michael W., et al. "Polarization in dynamic networks: A Hopfield model of emergent structure." *Dynamic Social Network Modeling and Analysis* (2003): 162-173.
- The role of social networks in natural resource governance: What relational patterns make a difference? Bodin and Crona 2009.

Week 11: Dynamics of Networks

Preferential attachment class of models. Master equations for the evolution of networks. Evolving robust and adaptive networks: lessons from protein-protein interaction networks

Readings:

- Network Dynamics by James Moody. In the Oxford Handbook of Analytical Sociology.
- Robust Control and Hot Spots in Dynamic Spatially Interconnected Systems, by Brock and Xepapadeas
- Excerpts of Albert, Réka; A.-L. Barabási (2002). "Statistical mechanics of complex networks" *Reviews of Modern Physics* **74**: 47–97.
- Hierarchical organization of modularity in metabolic networks by Ravasz, E., Somera, A.L., Mongru, D.A., Oltvai, Z.N., Barabási, A.L., 2002
- Wagner, Andreas. "Robustness and evolvability: a paradox resolved." *Proceedings of the Royal Society B: Biological Sciences* 275.1630 (2008): 91-100.

Week 12: Guest Lecture
TBA

Week 13: The Future of Complexity
How is complexity changing research, how it the research on complexity itself changing, and what are the major open questions in complexity and its applications.

Week 14: Project Presentations
Each student project team will give a presentation on their idea, work, and relevant literature.