Modeling Complex Systems (MTH401/MTH601)

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Monsoon 2015, Mon, Wed (11:30a-1:00p), TBD lecture hall
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Description Complex systems here imply systems that demonstrate unpredictable, sometimes fascinating, phenomena. Examples of such phenomena include synchronization in fireflies, schooling in fish, and formation of snowflakes. In complex systems a large number of components interact through simple rules to give rise to complex patterns, and yet, a small change in the rules can result in an entirely different outcome. In this course, we will use mathematical models to visualize such patterns, and isolate the key drivers of the final outcomes. Starting with the motivation on why we should model anyway, we will simulate examples of complex systems using population dynamics, self-propelled particles, networks, and cellular automata. The course will consist of weekly lectures and labs, and a final project where you will model and analyse a system of your choice. Knowledge of undergraduate level calculus, linear algebra, and basic programming (preferably in MATLAB) is required. The objective of this course is to help the student better understand the emergence of complexity in nature and developing the intuition to take a first crack at modeling a complex system.

Pre-requisites Undergraduate level differential calculus and linear algebra. We will also touch upon these briefly in the beginning of the course.

Learning outcomes

- Abstract a complex system into a simple mathematical form using meaningful assumptions
- Simulate and visualize complex dynamical phenomena including disease spreading, collective behaviour, vehicular traffic, and social networks
- Identify key driving points, properties and vulnerabilities of complex systems that can be used to predict qualitative outcomes

Text

There is no prescribed text for this course; we will be mainly using class notes and published papers. Material for this course has been borrowed with permission from Prof. David Sumpter at Uppsala University, Stockholm, Sweden. In addition, some relevant references are listed below:

- Boccara N. Modeling complex systems. New York, New York, USA: Springer
- Strogatz S. H. Nonlinear dynamics and chaos: with applications to Physics, Biology, Chemistry and Engineering. Cambridge, Massachusetts, USA: Westview Press
- Sumpter D. J. T. Collective animal behavior. Princeton, New Jersey, USA: Princeton University Press

Table 1: Schedule

Week	Representative examples/learning outcomes	Readings/videos
1	Why model? What is a complex system? / Mathematical preliminaries	–
2, 3	Epidemics, fads, voters, tipping points, rumours / Model and simulate changes in large populations using differential equations; abstract a large system using mean field approximation; plot bifurcation diagrams. hw 1 assigned	[10]
4, 5	Crowds, bird flocks, fish schools, insect swarms / Model human crowds, fish schools, and bird flocks as a system of self-propelled particles; describe long-term properties of such large collectives. hw 2 assigned	[4, 1, 12]
6, 7	Measuring complexity, information transfer / Compute entropy, Lyapunov exponents of a complex system; compute transfer entropy between two dynamical systems;	[14]
8	Midterm	–
9, 10	WWW, Facebook, power grid / Represent networks using graphs; describe network properties; identify key properties ; significance of scaling in networks. hw 3 assigned	[6]
11	Fireflies, epilepsy / identify nodes and connectivity for synchronization; controllability and observability of networks	[2, 3, 15]
12, 14	Cancer spread, traffic flow, seashells and snowflakes, cryptography, ants, forest fires / Use simple rules to simulate spatial relationships as cellular automata (CA), stigmergic behaviour in ants; use box-counting, kolmogorov complexity, and universal computing to analyze CA. hw 4 assigned	[13, 5, 11]
15, 16	Project presentations; reports due	–

Homeworks

There will be four homework assignments as part of this course. Those who register for MTH601 will get an extra homework problem each time. You are encouraged to collaborate on these, however, the work you submit should be entirely your own. No collaboration is permitted during the mid-semester exam, which will be conducted during Week 8. Please refer to academic dishonesty section below. 10% of maximum marks will be docked for late homeworks for every additional day; After three days no marks will be awarded.

Project

The course will end with a final project where you are encouraged to model and analyze a complex system of your choice, or, review and reproduce the results of a recent paper that models a complex system. The project topic or paper must be approved by the end of Week 10. At the end of the project you will be required to submit a 3 page report (including figures but excluding bibliography, and preferably in LaTeX) and present your findings before the class for 10 minutes. A detailed rubric for project grading will be shared after the midterm exam.

Grading

- Homework Assignments (4): 40%
- Midterm: 20%
- Project study: 40%

Office hours

Thursdays: 12–2pm

Academic dishonesty

Please carefully read http://www.iiitd.ac.in/education/resources/academic-dishonesty. Please discuss with me if you have doubts about what constitutes dishonesty, plagiarism, and cheating. You are responsible for your work!

References

[1] D. Helbing, I. Farkas, and T. Vicsek, Simulating dynamical features of escape panic., Nature, vol. 407, no. 6803, pp. 48790, 2000.

[2] Millenium Bridge (http://youtu.be/eAXVa__XWZ8)

[3] Steven Strogatz: How things in nature tend to sync up (http://youtu.be/aSNrKS-sCE0)

[4] http://www.red3d.com/cwr/boids/

[5] http://youtu.be/CgOcEZinQ2I

[6] A. D. I. Kramer, J. E. Guillory, and J. T. Hancock, Experimental evidence of massive-scale emotional contagion through social networks., Proc. Natl. Acad. Sci. U. S. A., vol. 111, no. 24, pp. 878890, 2014.

[7] A. Tsoularis and J. Wallace, Analysis of logistic growth models, Math. Biosci., vol. 179, no. 1, pp. 2155, 2002.

[8] http://youtu.be/dcMa0djC7IM

[9] http://math.colgate.edu/~wweckesser/math312Spring05/handouts/Nondim.pdf

[10] https://www.math.duke.edu/education/ccp/materials/diffeq/logistic/logi1.html

[11] http://youtu.be/E8kUJL04ELA,http://youtu.be/R9Plq-D1gEk

[12] http://angel.elte.hu/~panic/

[13] https://courses.cit.cornell.edu/bionb441/CA/

[14] Vicente, R., Wibral, M., Lindner, M. and Pipa, G. "Transfer entropy–a model-free measure of effective connectivity for the neurosciences." Journal of Computational Neuroscience, 2011, 30, 45-67

[15] Liu, Y.-Y.; Slotine, J.-J. and Barabsi, A.-L. "Controllability of complex networks" Nature, 2011, 473, 167-173