Introduction to Complex Systems

Instructor: Péter Érdi

Topic: The discipline of 'Complex Systems' studies discusses how collective behavior emerges from the parts of a system, due to the interaction between the system and its environment. You will learn the basic concepts and methods of complex system research. Both historical and present-day approaches will be mentioned. It will be emphasized that since many systems of very different fields, such as physics, chemistry, biology, economics, psychology and sociology etc. have similar architecture, very different phenomena of nature and society can be analyzed and understood by using a common approach called 'system thinking'.

Goal: The first goal is to teach WHY complex systems research is important in understanding the structure, function and dynamics of complex natural and social phenomena. The second goal is to give an introductory overview about HOW the fundamental methods of complex system research works. The course is not highly technical mathematically, but teaches and uses the basic mathematical notions of dynamical system theory (such as oscillation, chaos, fractals and so on.) Not only students of science majors, but social science students (with some mathematical interest and skill) are expected to take the class.

Course Structure:

Ten topics will be discussed. We shall spend one week on each topic. The three days will be dedicated to (i) conceptual approaches, (ii) mathematical tools, (iii) applications. Reading schedule: it is suggested that students read the text assigned before class each week. You should know that each topic is reviewed from the bird-eye perspective, and might be the subject of the whole course!

Exam: There will be a two hour long midterm and final written examination. If you are not satisfied with your grade, there is the possibility to improve your grade by an oral exam. Extra-class activities in connection with complex system research (e.g. writing of simulation programs, participation in class discussion, active participation in the events organized by the Center for Complex System Studies) will also be considered in assigning your final grade.

Topics and Readings: (the readings should be considered, as an intellectual background material, and they contain obviously much more than the present course material! More specific readings will be discussed with each student individually.)

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1. COMPLEX SYSTEMS: CONCEPTUAL INTRODUCTION

Topics: What are the characteristics of simple and complex systems? Structural, functional, dynamic and algorithmic complexity.
Complexity in physics, biology, economics, and sociology.

Readings: + Waldrop, MM: Complexity: the Emerging Science At the Edge of Order and
2. HISTORY of COMPLEX SYSTEM RESEARCH

Topics: Some fundamental theories of the 20th centuries are reviewed: System theory, Cybernetics, Theory of Dissipative Structures, Synergetics and Catastrophe Theory.


3. COMPETITION and COOPERATION; the VOLTERRA - LOTKA WORLDS and BEYOND

Topics: The Volterra-Lotka model has its roots in chemistry and ecology. It can be used, however, as a general paradigm of systems with competitive and cooperative interactions. The mathematics of oscillation. Chemical, ecological and socioeconomic applications.


4. CHAOS and FRACTALS in NATURE and SOCIETY

Topics: Chaos and fractals proved to be very efficient mathematical concepts to understand temporal and spatial complexity. Elementary mathematical explanation. Chaos in chemistry, population dynamics, brain and economics. Fractals in physiology. The fractal nature of organizations.


5. SELF-ORGANIZATION and SELF_ORGANIZED CRITICALITY

Topics: Self-organization is a vague concept in many respects, still a powerfull notion of modern science. Specifically and counterintuitive, noise proved to have beneficial (seomtimes indispensable) role in constructing macroscopically ordered structures. Elementary mathematical models of noise-induced ordering.

In physics, a critical point is a point at which a system radically changes its behavior or structure, for instance, from solid to liquid. In standard critical phenomena, there is a control parameter which an experimenter can vary to obtain this radical change in behavior. In the case of melting, the control parameter is temperature. Self-organized critical phenomena, by contrast, is exhibited by driven systems which reach a critical state by their intrinsic dynamics, independently of the value of any control parameter. The archetype of a self-organized critical system is a sand pile. Sand is slowly dropped onto a surface, forming a pile. As the pile grows, avalanches occur which carry sand from the top to the bottom of the pile. At least in model systems, the slope of the pile becomes independent of the rate at which the system is driven by dropping sand. Self-organized criticality is a useful concept and was used to explain statistical features for a wide variety of open systems with many components, ranging from geology to biology and economics. A few illustrative example will be given.

Readings:


6. GAME THEORY, EVOLUTION, ECONOMICS

Topics: Game theory emerged as an important tool for treating the problem of necessary cooperation to avoid (nuclear and other) catastrophes. The most famous game is the Prisoner Dilemma. The fundamental types of games will be discussed. Illustrative examples of applications for evolutionary theory and economics will be given.


7. NETWORKS EVERYWHERE: FROM MOLECULAR to SOCIAL
Real world systems in many cases can be represented by networks. Networks can be seen everywhere (neural networks of the brain, food webs, ecosystems, electric power networks, system of social connections, global financial network, the world-wide web). Since the famous social psychological experiment of Stanley Milgram, it is known that from a certain point of view we live in a 'small world.' However, the relationships between the structure of large networks and their dynamical properties generally are not well known. The performance of many biological, ecological, economical, sociological, communication and other networks can be illustrated by using new approaches coming from graph theory, statistical physics and nonlinear dynamics. Examples will be given to illustrate the power of the new approaches in the understanding of the organization of social structures. Specifically, scientific collaboration networks will be analyzed.

+ Hayes B: Graph Theory in Practice: Part I, II
American Scientist 88(1) and 88(2)2000


8. COMPLEXITY of the BRAIN

Topics: It is often said in a colloquial sense that the brain is a prototype of complex system. Several different notions of complexity may be more formally related to neural systems. First, structural complexity appears (i) in the arborization of the nerve terminals at the single neuron level, (ii) in the complexity of the graph structure at the network level, and (iii) in the systems of networks forming closed loops of closed loops. Second, functional complexity is associated with the set of tasks performed by the neural system. Third, dynamic complexity can be identified with the different attractors of dynamic processes, such as point attractors, closed curves related to periodic orbits, and strange attractors expressing the presence of chaotic behaviour.

Readings:


9. SOCIODYNAMICS: HOW TO BUILD MODELS TO UNDERSTAND EPIDEMICS, ARM RACES, WARS, AND EPIDEMICS?

Topics:

Simple models can illuminate essential dynamics of complex, and crucially important social systems. Models of war and arm races can be constructed within the framework of the Volterra-Lotka model

10. Complexity researches: where we are now?

Summary. Open discussion forum. Preparation for the exam.