Complex Systems: An Introductory Workshop

St Stephen's College, Delhi, 19 Oct - 24 Oct, 2026

Lecture Abstracts

Study of Complex Systems: Search for New Paradigm(s)

Dr Sanjay Kumar

Department of Physics, St Stephen's College

(9:30-11:00, 19 October, 2026)

A paradigm for a field of scientific research is a set of concepts, associated theories, methods of validation and experimentation, and measurement techniques shared by the community of scientists, and which provide a framework for doing research. Complex systems show novel features like self-organisation and emergence which have been rarely studied in traditional sciences. Since analytical solutions can be found for only very simple models of complex systems, the validation of models and prediction rely mostly on computational algorithms. This complicates the notion of empirical validation, which has formed the basis experimental sciences so far. Are studies of complex systems moving towards a new paradigm of scientific research? It will be argued that the immense diversity of complex systems studied, which range from artificial algorithms to society based economic and traffic systems to biological systems and planetary climate, make it impossible to decipher a single paradigm applicable to studies of all complex systems. The study of complex systems seems to be rather challenging longstanding 'orthodoxies' of traditional sciences. Notions of context independent universal laws and bottom-up causality, and exclusionary understanding of randomness and determinism, do not hold for complex systems.

The Mathematics of Growing-Dividing Systems and the Puzzle of Self-reproduction

Dr Parth Pratim

School of Advanced Engineering, UPES, Dehradun

(11:30-13:00, 19 October, 2026)

Self-reproduction in living systems, such as bacteria, exemplifies remarkable regulation wherein thousands of intracellular chemical components synchronize their highly nonlinear and decentralized dynamics so that their abundances double in unison. How such *balanced growth* emerged in primordial chemical systems and persists in modern cells remains a fundamental puzzle. In this lecture I will first introduce a mathematical framework, Growth-Division Dynamics, for studying open systems such as growing-dividing bacterial cells. Applying this framework to simple mathematical models of cells, I will show that the global regulation required to achieve balanced growth can emerge spontaneously through repeated cycles of growth and division, without the need for the sophisticated regulatory

circuitry found in modern cells. This powerful and robust mechanism provides a potential explanation for the emergence of *compositional homeostasis* and may represent a primitive regulatory mechanism shared between modern and primordial cells. I will then address a related mathematical puzzle: the emergence of exponential growth in highly non-linear chemical dynamics. Why do intracellular chemical populations grow as a simple exponential function of time (all with the same growth exponent) within a cell-cycle generation, even though their underlying chemical kinetics are highly non-linear? I will show that this remarkably simple behaviour emerges when a dynamical system, irrespective of its nonlinearity, satisfies a special mathematical condition known as the degree-I homogeneity. Together, these results illustrate how simple mathematical principles can give rise to complex biological organization and reveal the underlying order in nonlinear dynamical systems.

Self-Organization, Innovation and Collapse: Evolution of a Complex Network

Prof Sanjay Jain

Department of Physics and Astrophysics, University of Delhi

Santa Fe Institute, Santa Fe, New Mexico, USA

Physics Department, Ashoka University, Sonepat, Haryana

(9:30-11:00 and 11:30-13:00, 20 October, 2026)

Complex systems, including living organisms, ecosystems and societies, typically have an underlying complex network of interacting components.

A brief introduction to the role of networks in complex systems will be given. Graph theory, the branch of mathematics that describes networks, will be introduced. During the course of their evolution, complex systems including organisms, civilizations and the biosphere as a whole, exhibit the growth of complexity, its persistence, and on a certain timescale, its collapse. Understanding these features is an important goal of complex systems research. We will discuss an idealized mathematical model of network evolution that shows all these features under one roof. The simplicity of the model allows us to gain some insights into these phenomena. We will discuss how these insights could be relevant for understanding the origin of life and the collapse of societies. Innovations play a crucial role in the evolution of complex systems. If time permits, we will discuss how ‘innovation’ can be defined mathematically in the model and how innovations cause the growth, maintenance and collapse of complexity in the model.

From Stability to Chaos: Understanding Dynamical Systems

Dr Akshay Rana

Department of Physics, St Stephen’s College

(9:30 – 11:00 and 11:30- 13:00, 21 October, 2026)

These lectures introduce dynamical systems as a framework for understanding how physical systems evolve in time. We explore continuous systems described by differential equations and discrete systems governed by iterative maps, using examples such as nonlinear oscillators and the logistic map. Topics include fixed points, stability, phase portraits, limit cycles, bifurcations, period doubling, and chaos. Through analytical reasoning and numerical illustrations, the lectures show how simple deterministic rules can produce rich and complex behaviour.

Learning by Listening: An Introduction to Reservoir Computing with Echo State Networks

Dr Abhinav Gupta

Department of Physics, St Stephen's College

(9:30-11:00, 11:30 – 13:00, 22 October, 2026 , and 9:30-10:30, 23 October, 2026)

When only a single quantity of a complex system can be measured, how much can that one recording reveal about everything left unmeasured? Remarkably, under suitable conditions, the history of a single signal can contain enough information to reconstruct the system's hidden dynamics. Echo state networks offer an ingenious way to exploit this insight. A fixed, randomly connected network listens to the signal, gradually building a memory of what it has heard. A simple trained readout can then use this memory to estimate hidden quantities and predict future behaviour. Through short lectures and hands-on computational experiments, these sessions explore the mathematical ideas behind this remarkable approach to learning from dynamical systems.