HANDS-ON RESEARCH IN COMPLEX SYSTEMS SCHOOL

Shanghai Jiao Tong University
17-29 June 2012

LABORATORY SESSIONS

[A] Flow and rearrangements in viscoelastic materials

Prof. Eric Weeks and Xia Hong (Emory University)

Why do butter, lotions, and creams act like both liquids and solids? What causes foam to flow differently from paste? These types of questions are at the heart of soft condensed matter, the study of materials with both fluid and solid properties (often called "complex fluids"). Moreover, the mechanical properties and ability to flow are in fact the defining features of soft materials, and are key to the practical utility of soft materials. In this module, we will use a microscope to observe the flow of an emulsion, made of oil droplets in water. Students will build simple flow chambers and observe how the behavior depends on the flow details (for example, flowing around corners or through constrictions). The deformation of the droplets from perfect spheres lets us determine the forces the droplets feel. We will take movies of these flows and analyze the movies to relate droplet forces to their motions.

[B] Measuring normal modes in 2D colloidal systems

Prof. Lei Xu and Dr. Peng Tan (The Chinese University of Hong Kong).

At first glance, most solids seem rigid and hard to deform. However, when zooming in to inspect their basic building blocks - atoms, they are all constantly vibrating around equilibrium positions. These vibrations are the superposition of the normal modes at different frequencies. Each normal mode vibrates at tiny amplitude and high frequencies such that even the fastest and most powerful microscope can not resolve. Yet they determine crucial properties of solids, such as how fast solids can warm up and cool down, or how does sound travel in the materials. Therefore, the understanding of solids can be greatly improved, if we can directly “watch” these vibrations. Using micron sized particles as large “atoms”, we build 2D colloidal systems whose motions can be directly visualized. From these motions, the normal modes can be extracted at single-particle level.

[C] Shapes Analysis in Cell Migration

Prof. Erin Rericha and Jie Zhao (Vanderbilt University)

The classic model of rapid ameboid cell migration in two dimensions describes a cell moving forward by extending protrusions in the front and using muscle-like contractions to retract the back. How the cell establishes where to protrude and where to contract, *cell polarity*, is an active area of research at the interface of biology and nonlinear dynamics. Indeed, recently the field has embraced that the cell components responsible for steering the cells form an excitable system, and can support waves, multiple pseudopod dynamics, etc. detectable by measuring the time dependent shape of the cell's perimeter.

Using the model single cellular organism, *Dictyostelium discoideum*, we will investigate how the cell shape changes as it migrates without any external cues and when exposed to switchable chemical signals. We will use time lapsed fluorescent microscopy to record a movie of the migrating cell and extract the cell shape with custom interface finding matlab code. We will compare the results to prior solutions of cell shape predicted from a model of the underlying excitable system. Time and interest permitting we can also compare the cell behavior in the presence of drugs that alter the underlying excitability.

[D] Synchronization in Populations of Chemical Oscillators:
Dr. Mark Tinsley, Professor Kenneth Showalter, and Simbarashe Nkomo (West Virginia University).

Populations of coupled oscillators are common in physical, chemical, and biological systems. The Belousov-Zhabotinsky (BZ) reaction proves to be a particularly amenable system for the study of large populations of oscillators. In our experiment, each individual oscillator consists of a small (50 - 200 μm) catalyst-loaded bead. When placed into a catalyst-free BZ solution, these beads can be maintained in an excitable or oscillatory state. Global coupling of such systems can be realized by stirring a suspension of the beads, and in unstirred systems, diffusion leads to local coupling. More complex networks of coupling may be realized by using a photosensitive catalyst and light-mediated feedback between the beads.

The microbeads exhibit periodic oscillations or stationary state behavior, which will be monitored at the characteristic wavelength of the catalyst. Following the identification of the location of a bead, the frequency and phase distributions will be determined from the time series of the grayscale intensity. All image analysis and data processing will be carried out using Matlab. At low number densities, the beads are effectively independent oscillators, and at higher densities, local coupling of the oscillators may occur. Phase and frequency information for each oscillator may then be used to investigate various entrainments which occur as a function of number density.

[E] Mechanical oscillations in regeneration and locomotion
Dr. Eva-Maria Schoetz (Princeton University) and Sofia Quinodoz (Princeton University) and Kristine Glauber (University of California Irvine)

The interplay of cell mechanics and cell signaling plays a major role for tissue specification and pattern formation during embryonic development and regeneration. In this session, we will study mechanical oscillations that occur during regeneration and locomotion in two popular regeneration model systems: hydras and planarians. We will build simple experimental setups that allow us to study these oscillations in real time. Using time lapse imaging and image analysis in MATLAB, we will determine the frequency and spatial pattern of these oscillations and manipulate the parameters (e.g. frequency, duration, amplitude) experimentally to gain a better understanding of their biological origin.

[F] *Nonlinear dynamics of coupled nonlinear electronic oscillators*
Dr. Gautam C. Sethia, and Mr. Mitesh S. Patel (Institute for Plasma Research, India)

The dynamics of single and coupled nonlinear electronic circuits will be explored through both simulation (using ORCAD-PSPICE) and experiments. An introduction to circuit simulation and to analysis software will be followed by the use of the software in designing and simulating some simple electronics circuits (e.g., clipper, clamper, amplifier). These steps will familiarize students with the basic building blocks necessary for the design and simulation of classic systems such as the Chua, Lorenz and Roessler models. Phenomena such as period doubling, period adding, and bifurcation routes to chaos will be studied using a digital oscilloscope and will be compared to numerical simulations conducted using XPPAUT. Synchronization and antiphase oscillations will be studied using coupled Chua oscillators.

[G] Using Programmable Microcontrollers (the Arduino) in Tabletop Experiments

Professor Thomas E. Murphy, Hien Dao, and Caitlin Williams (University of Maryland)

Digital microprocessor systems are ubiquitous in consumer electronics today, and are found in automobiles, computers, embedded systems, handheld devices, and smart sensors. Because of their flexibility, programmability and functionality, microprocessor systems have replaced many formerly analog circuits, including dynamical systems such as feedback control loops.

In this session, participants will learn some simple techniques for programming and controlling a simple microcontroller board, the Arduino. Arduino is an inexpensive and open-source circuit board that allows hobbyists and scientists to quickly and easily experiment with microprocessors. The Arduino board is controlled using simple and intuitive C-language programs that are created, compiled and debugged using a freely-available integrated development environment.

We will also demonstrate some common uses of the Arduino to control actuators and read sensors, and we will discuss some simple audio signal processing functions including time-delay and filtering. Building on this, we will develop and explore nonlinear systems with time-delayed feedback. Experiments will be compared with Matlab simulations to study the dynamical behavior using phase space portraits and bifurcation diagrams.

[H] Instabilities in a Fluid Flow

Professor Harry Swinney, Dr. Bruce Rodenborn, and Dr. Likun Zhang (University of Texas) and Yorquant Wang (Shanghai Jiao Tong University)

Flow between concentric independently rotating cylinders has become a paradigm for the study of instability in fluid dynamics and other systems. If the inner cylinder speed is increased slowly from rest, when a well-define rotating rate is reached the flow will make a transition from one with no pattern to a state with toroidal (donut-shaped) vortices wrapped around the inner cylinder and stacked along the axis. At higher rotation rates transitions occur to increasingly complex flows.

Participants will use an inexpensive digital camera (webcam) to make movies of the flow patterns and then will use Matlab to analyze the movies to characterize dynamical states of the flow. The power spectral and dynamical systems techniques used to identify transitions in the dynamics, from simple periodic states (limit cycle attractors) to chaos (strange attractors), are applicable to diverse systems (chemical, mechanical, fluid, physiologic signals, etc.)

[I] Boolean Network Dynamics

Professor Dan Lathrop, assisted by David Meichle (University of Maryland)

This lab session will focus on the dynamics of electronic boolean circuits. Logic gates are used in all of our digital electronic tools. We will explore unusual arrangements of these logic gates, relative to normal electrical engineering circuits, that incorporate loops in more general topological connections. In standard engineering design, all information feeds forward in a very deterministic way. By contrast, these unique circuits have loops in their connections, causing a wide variety of dynamical states, including stationary states, oscillatory states, chaotic states, and the ability to synchronize various subsystems. We will utilize such hands-on skills as building logic circuits and high-speed electronic diagnostics, and will deploy the scientific method in our study of these dynamics.

[J] Dynamics of Locomotion

Professor Daniel I. Goldman, Nick Gravish, and Sarah Sharpe (Georgia Institute of Technology

Organisms from six legged cockroaches to two legged humans display similar dynamics when walking and running. Below a non-dimensional speed (the Froude number), dynamics can generally be modeled as an inverted pendulum, while above, dynamics can be modeled as a spring-mass system. Walking as an inverted pendulum can save energy through trading potential and kinetic energy at each step. Bouncing during running in larger organisms allows for storage and return of energy using elastic elements in limbs like tendons. The transition is in part a result of the inability of gravity to supply enough force to accelerate the body downward for sufficiently large walking speed.

The Hands-On project's goal will be to measure level locomotion dynamics during walking and running of a large biped (a human) to illustrate concepts in biomechanics. Forces will be measured during locomotion using a custom-built three-axis force platforms while simultaneously measuring kinematics using high speed digital imaging. The force and video data will be analyzed in Matlab/Scilab and with custom tracking software. Physical and numerical dynamical models of walking and running will be constructed and analyzed, and will be used to compare to experimental observations, including force patterns and stability criteria.

[K] Turbulence: Flow analysis by imaging particles

Professor Michael Schatz (Georgia Tech, Atlanta, Georgia), Balachandra Suri, and Jeffrey Tithof (Georgia Tech)

Turbulent flows play a central role in many natural and technological processes; developing a fundamental understanding of turbulence stands as one of the greatest challenges in physics. This Hands-on Session will explore the problem of turbulence in table-top experiments on two dimensional (2D) flows. The simple design of the experiments will enable Hands-on participants to learn quickly essential techniques that permit exploration of scientific questions at the forefront of turbulence research.

Turbulence has long been associated with the idea of fluid flow that is irregular and unpredictable. However, decades of experimental observations demonstrate that characteristic patterns arise repeatedly. Numerous empirical methods have been devised to characterize these patterns, known as "coherent structures"; recent theory suggests that coherent structures observed in experiments are closely related to special unstable solutions (e.g., fixed points and periodic orbits) in the fluid equations (the Navier-Stokes equations). Firm evidence supporting the connection between these unstable solutions and experimentally-observed coherent structures has not yet been found. The Hands-on experiments will search for such evidence by visualizing 2D fluid flows using tracer particles. Movies of the visualized flow will be recorded using standard web cameras. The velocity fields of the turbulent flow will be extracted from the movies by the widely-used technique of particle image velocimetry (PIV). The velocity fields will be examined for evidence of the existence of unstable fixed-point and periodic-orbit solutions.

The results of the experiments will be compared to the numerical model of flow turbulence which will be developed in the hands-on session led by Brian Storey. Participants interested in this experimental session are encouraged to attend to Professor Storey's session as well.

[L] Micro-mirror Spatial Light Modulators: Image Processing and Simulation of Spatiotemporal Dynamics of Excitable Media

Professors Rajarshi Roy (University of Maryland), Xiaowen Li (Beijing Normal University), Aaron Hagerstrom and Jiang Xu (University of Maryland)

A spatial light modulator(SLM) [1] that utilizes 480x320 micromirrors for spatiotemporal modulation of a light beam is incorporated as part of a feedback loop composed of a laptop computer and a digital camera [2]. The computer updates the state of the spatial light modulator based on input from the camera. Thus one may progressively iterate an image according to an algorithm that may be programmed as desired, and watch spatial pattern formation in real time on the computer screen. We can explore different update procedures, including the well-known Greenberg-Hastings rules [3], and a simple integrate and fire model, both of which simulate the spatiotemporal dynamics of excitable media [4]. The effect of varying parameters that set the firing threshold, refractory period and spontaneous noise component can change the images dramatically and one may see various classes of wavefronts and patterns generated. Global coupling and community structure can also be implemented, leading to oscillatory dynamics.

We will present two configurations of this equipment. First, we will use the SLM and a webcam without any modifications. Our excitable media model will be projected onto a screen, and imaged using a webcam forming a feedback loop, allowing for an intuitive and interactive exploration of the model's dynamics. In the second configuration, we have removed the projection optics from the SLM so that the mirrors are exposed. Likewise, the imaging optics have been removed from the camera. We illuminate the SLM with light from a green laser pointer, and arrange the camera so that the diffraction pattern generated by the SLM lands on the camera's detector. This diffraction pattern is then fed back to the SLM, again using an excitable medium model. Our goal is to explore the spatiotemporal dynamics that may be generated though different feedback algorithms based on models of excitable media.

[1] http://www.digikey.com/product-highlights/us/en/texas-instruments-dlp-technologies/688; http://www.ti.com/lit/an/dlpa021a/dlpa021a.pdf
[2] http://www.logitech.com/en-us/435/6816
[3] J. Greenberg, B. Hassard, and S. Hastings, SIAM J. Appl. Math. **34**, 515 (1978); M. Gerhardt, H. Schuster, and J. J.Tyson, Science **247**, 1563 (1990); R. Fisch, J. Gravner, and D. Griffeath, Stat Computing **1**, 23 (1991).
[4] http://en.wikipedia.org/wiki/Excitable_medium . See also Daniel Kaplan and Leon Glass, *Understanding Nonlinear Dynamics* (Springer, 1995)

MATHEMATICAL MODELING

The modeling sessions may be taken in any order, except that participants not familiar with MATLAB should take the *Introduction* session before taking other modeling sessions.

Modeling senior faculty:
Professor Mark Shattuck (City College of New York), (coordinator of modeling sessions
Professor David Cai (Shanghai Jiao Tong University)
Professor Qi Ouyang (Peking University)
Professor Brian Hunt (University of Maryland)
Professor Brian Storey (Olin College, Massachusetts)

[M] Introduction
Led by all modeling faculty

This session will introduce participants to some basic and intermediate MATLAB skills for data analysis and modeling using a "double pendulum" as an example system. The double pendulum is a simple physical system that behaves "chaotically": it is very unpredictable until friction dissipates most of its energy. Using a digital camera, we will make a movie of the apparatus. Participants will learn to extract system state information (position and velocity) from the images and compare the data with computational results from a mathematical model. Modules ranging from introductory to more advanced will be provided so that participants with or without MATLAB experience can start at an appropriate level.

[N] Introduction to computational fluid dynamics and turbulence
Professor Brian Storey and Jacqueline Baca (Olin College)

The equations which govern the motion of fluids, the Navier-Stokes equations, are useful for describing a number of important problems in science and engineering. The Navier-Stokes equations are non-linear equations which are mathematically very challenging to solve, thus computational fluid dynamics (CFD) is an important tool for many fields. Utilizing MATLAB, we will introduce some simple methods for modeling 2D turbulent fluid flows. The participants will write their own simulation from scratch. While CFD is a vast field with numerous commercial or open-source codes available; by writing our own simple simulator we can learn a number of important concepts which are useful even when utilizing a commercial CFD code.

The results of the simulation will be compared to the experiments which will be conducted in the experimental hands-on session led by Mike Schatz. Participants interested in this modeling session are encouraged to also attend to associated experimental session. No knowledge of fluid dynamics or MATLAB is required. We will only assume some basic knowledge of vector calculus and linear algebra.

[O] Modeling Dynamical Systems
Professor Brian Hunt and Likun Zhang (University of Maryland)

Participants will learn about model development, analysis, and interpretation of computational results using a variety of mathematical models. Our main focus will be on models that are ordinary differential equations, and participants will gain practice in using MATLAB's differential equation solvers. Participants can choose among the following examples (or participants can also suggest systems they are interested in modeling)

(1) Dynamics and bifurcation diagrams for low-dimensional chaotic models;
(2) Spatiotemporal chaos and predictability in a (very) simplified weather model;
(3) Modeling the human immune system.

[P] Molecular Dynamics
Professor Mark Shattuck and Aline Hubard (City College of New York)

This session will introduce the participants to the basics of Molecular Dynamics (MD) using MATLAB. A Molecular Dynamics code solves Newton's laws for a collection of particles or molecules. We will discuss the advantages/disadvantages to using MATLAB as compared with traditional programing languages like C/C++, Fortran, or Java. Each participant will develop his or her own simple MD simulator using less than a page of Matlab code. We will then add more advanced features like better integrators (Velocity Verlet, Gear Predictor/Corrector) and important code acceleration techniques like cell-list and Verlet list. More advanced participants may work on event-driven codes including delayed-states algorithm during this session or during an extended session.

NOTE: the following two sessions will be only available in the second week:

[Q] Mathematical Modeling of Biological Systems (25, 26, and 27 June)
Professor Qi Ouyang, Jia Che,n and Bin Chao (Peking University)

This session is for those who are interested in applying physics principles and quantitative methods to quantitative systems biology. The session will focus on how to simulate the dynamic behavior of a biological genetic control network that can perform certain functions. Three topics will be discussed in this session:

(1) Simulating the network behavior Boolean dynamics models, and study of the dynamics properties of the systems, such as attractors, trajectory, stabilities. The biological meaning of these properties will be discussed.
(2) Simulating the network behavior using ordinary differential equations. Certain nonlinear dynamics concepts will introduced during the study. Such as phase space description of the dynamic systems, limit cycle, Hopf bifurcation, saddle-node bifurcation. How the biological systems use these properties to construct a stable control network will be discussed.
(3) Reverse Engineering. Given a biological function, how to find a suitable network that can robustly perform the function will be the focus here. Logic deduction method will be applied in this study. The functional constrain on network topology will be discussed.

[R] Modeling of Neural Networks
Professors Douglas Zhou and David Cai (Shanghai Jiao Tong University)

This lecture focuses on the fundamental dynamics of neurons. It covers the following topics:

(1) The introduction of neuronal system and the classical Hodgkin-Huxley and other related neuronal models.
(2) The phase plane analysis of neuronal models such as the Hodgkin-Huxley neuron.
(3) The dynamics of Hodgkin-Huxley system under external drive such as sinusoidal current.
(4) Hands-on investigation of the period-doubling route to chaos in this neuronal dynamics.