Description of Hands-On Sessions

Hands-On Research in Complex Systems School
Universidade Federal do ABC
Santo André, Sao Paulo, Brasil
27 July – 6 August 2009

1. 2-Dimensional turbulence
Professor Michael F. Schatz (Georgia Institute of Technology),
Jennifer Rieser (Cornell University), and Dr. Carlos Jose Amado Pires (UFABC)

Turbulence, one of today's great unsolved problems in physics, has long been associated with flow behavior that is irregular and unpredictable. However, decades of experimental observations demonstrate that characteristic flow patterns arise repeatedly in turbulence. Numerous empirical methods have been devised to characterize these patterns, known as "coherent structures"; however, recent theory suggests that coherent structures observed in experiments are closely related to unstable solutions in the fluid equations (the Navier-Stokes equations). Firm experimental evidence supporting the connection between unstable solutions and coherent structures has not yet been found. Participants in this Hands-On session will have an opportunity to participate in original experimental research that seeks to bridge the gap between theory and experiment.

The Hands-On experiments will examine quasi-2D flows for evidence of unstable periodic solutions using inexpensive equipment. Turbulence theory to date has focused on flows in 3D (pipe flow, plane Couette flow); clear experimental evidence requires measurements of 3D time-dependent velocity fields, which push the limits of today's experimental capabilities. By contrast, measurements of 2D velocity fields can be readily performed on simple table-top experiments. Participants will learn to set up and to visualize flow patterns in electromagnetically-driven quasi-2D flows. Images of the flow will be acquired using web cameras; velocity fields will be obtained from the images using techniques of Particle Image Velocimetry. The resulting velocity data will be analyzed by means of recurrence plots to search for evidence of unstable time-periodic solutions. The Hands-On session will use MATLAB; however, alternative image acquisition and analysis methods that use free or open source software will be discussed. Results from the Hands-On experiments may stimulate future theory, thereby helping to advance our understanding of turbulence.

2. Coarsening of Shaving Foam
Professor Nicolás Mujica and Leonardo Gordillo (Universidad de Chile), and
Dr. Diego Marconi (UFABC)

Foams are a collection of highly packed bubbles within a complex liquid matrix. Despite being made almost completely of gas (about 95%), foams behave like elastic solids when deformed gently and flow like a liquid when stresses are higher. Foams are important for many industrial applications, like fire-retardant foams; however, their basic physics is still not understood. Being able to predict their elastic or flow-like properties from their structure is still impossible.

Sound propagation through bubbly liquids has attracted much attention. The presence of gas bubbles in a liquid profoundly affects its acoustic properties. In particular, a very low speed of sound can be reached, which can be lower than both sound speeds of each phase. This reduction is due to the high contrast of acoustic properties: the density of the mixture is dominated by the density of the liquid, and its compressibility is given by that of the gas. In contrast to bubbly liquids of small gas volume fraction, very little work has been done on sound propagation through foams. An important characteristic of foams is that they are never in equilibrium. They are intrinsically unstable and evolve in time, by one or more of the following aging mechanisms: (i) liquid can drain due to gravity (ii) the liquid film that separates two bubbles can become too thin and, consequently, unstable, causing film rupture and bubble coalescence; (iii) gas can diffuse through the liquid film from one bubble to another. In some cases (e.g., shaving foam), the dominant aging mechanism is the gas diffusion between bubbles.

In this session participants will learn about wave propagation in random media. We will measure the time evolution of the effective sound speed in coarsening shaving foams using a pulse propagation technique. A computer generated pulse-shaped signal will be amplified and emitted by a loudspeaker in contact with a column of foam placed in a cylinder. A series of small microphones will be placed in the cylinder inner wall, and the propagating acoustic signals will be acquired to a computer. The data will be analyzed using MATLAB and a standard cross correlation algorithm. Even in the long-wavelength limit the effective sound speed in foam depends on its micro-scale structure. This intriguing result will be explained by considering the foam liquid-matrix elasticity.

3. Nonlinear Dynamics and Chaos in a Time-Delayed Electro-Optic Feedback System

Professor Rajarshi Roy, Adam Cohen, and Bhargava Ravoori (University of Maryland), and Dr. Tiago Pereira (UFABC)

Non-linear systems with self-feedback are known to demonstrate a rich variety of behavior ranging from simple oscillations to very fast chaos as parameters such as the feedback strength, delay, and signal bandwidth are varied. Several physical realizations of such systems are possible. Electro-optics systems have a wide operational bandwidth while being easily controllable. We will provide the participants with the opportunity to experiment with an electro-optic system and observe the route to chaos.

Our system consists of a semiconductor laser (commercially available and commonly used in telecom) emitting infrared radiation at 1550 nm that is fiber-optically coupled to a Mach-Zehnder electro-optic modulator. This modulator is the heart of the loop, and has a nonlinear optical transmission output characteristic as an electronic input is varied. The optical output of the modulator is converted into an electronic signal by a photo-receiver, which is amplified before being fed back to the modulator. We will observe how the dynamics of the system change as the feedback strength and time delay are varied.

The participants will vary the feedback strength and make a bifurcation diagram as they do this. This pictorial depiction of the dynamics of the system sheds light on the parameter ranges over which the system displays a variety of dynamical behavior. A mathematical model of the system will be introduced. Numerical simulations of this model, programmed in MATLAB, will be shown to be a powerful tool in understanding the dynamics of the system. Bifurcation diagrams, Lyapunov exponents, as well as synchronization of experimentally measured and model dynamics will be explored. Applications of the system to communications and sensing will be discussed.

4. Instabilities in Flow between Concentric Cylinders

Professor Harry L. Swinney and Bruce Rodenborn (University of Texas), and
Dr. Cayo Prado Fernandes Francisco (UFABC)

Flow between concentric independently rotating cylinders has become a paradigm for the study of instability in fluid dynamics and other systems. The primary instability that occurs in flow between rotating cylinders with increasing inner cylinder rotation rate (if the outer cylinder is at rest) leads to axisymmetric toroidal shaped vortices, discovered by G. I. Taylor in 1923. In recent years, a variety of higher instabilities has been discovered, some of which will be examined in this Hands-On session.

Participants will learn about dynamical instabilities and their characterization by using an inexpensive digital camera to obtain movies of flow patterns as a function of inner cylinder rotation rate. The flow patterns will be made visible by suspending small flat flakes into the fluid. Participants will analyze the movies using MATLAB to identify transitions (bifurcations) and to characterize the increasingly complex dynamics. Topics that will be discussed include multiple stable states, quasi-periodicity, analysis of power spectra, construction of phase space attractors by the time delay method, types of attractors (limit cycles, tori, strange attractors), chaos, fractal dimension, and Lyapunov exponents.

5. Vibrated Granular Materials

Professor Mark D. Shattuck (City College of New York) and
Dr. Ebert Macau (INPE, San Jose dos Campos, Brasil)

Granular materials such as sugar and sand are important in industries ranging from food processing to construction to pharmaceuticals, yet a fundamental understanding of granular systems, comparable to the understanding of fluids and solids, does not exist. Such an understanding could have far reaching implications. In this session the dynamics of a granular system will be studied in two dimensions, where each particle can be imaged and tracked to obtain the microscopic trajectories. The experiment will use spherical stainless steel ball bearings of diameter D = 3.175 mm in a container 17.5 D wide by 20 D tall by 1.0 D deep. A thin plunger slides through a slot in the bottom of the cell and oscillates sinusoidally to excite (heat) the particles from below. A freely floating weight confines the particles from the top, allowing the volume to fluctuate but providing constant pressure conditions.

This system shows a number of interesting behaviors, including a first-order phase transition, shock waves, and quenching and annealing cycles. With this system, we will explore computer control using a sound card, optimal lighting techniques, and digital image acquisition. The images will be analyzed using MATLAB to locate and track particles. We will learn how to generalize these techniques to more complicated image tracking. Time-dependent density fields and radial distribution functions will be extracted from the data and interpreted in terms of concepts from statistical mechanics.

6. Synchronization in Populations of Chemical Oscillators

Professor Kenneth Showalter and Dr. Mark Tinsley (West Virginia University), and Dr. Anderson Ribeiro (UFABC)

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 intensity feedback between the beads.

The micro-beads exhibit periodic oscillations when placed in the catalyst-free BZ solution, which will be monitored at the characteristic wavelength of the catalyst. At low bead densities, the beads are effectively independent oscillators. 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 higher densities, local coupling of the beads may occur. Phase and frequency information for each bead may then be used to investigate the various entrainments which occur in the system as a function of local bead density.

7. Nonlinear Dynamics of Animal Locomotion

Professor Daniel I. Goldman and Nick Gravish (Georgia Institute of Technology), and Dr. Elizabete Lima (UFABC)

Terrestrial biological movement of animals like lizards and spiders is the result of coordination of multi-scale (ion channels to muscle to toes), multiple degree of freedom, nonlinearly coupled elements which must interact with complex environments like sand, leaf litter and tree bark. Recent experimental and theoretical work indicates that while nervous system control is important to maintain performance (speed, stability) during locomotion, the role of the mechanics of the organism cannot be neglected. For example, stability of cockroach locomotion at high speed on flat ground (>10 body-lengths/sec, 20 steps/sec) can be predicted by a minimal feed-forward model which neglects any active control and relies on the asymptotic stability properties of mass-spring models. Thus, the short-time (few steps) stability of the cockroach on level ground is likely a consequence of its lateral oscillation generated by two limbs pushing against a third on the opposite side of the body at each step. It is hypothesized that lateral oscillation during locomotion is important for stability of sprawled-posture organisms during running on ground of different orientation; lateral oscillation of similar magnitude is observed in vertical climbers like cockroaches and geckos.

In this case, the net lateral forces are generated by limbs pulling the organism side-to-side.

The Hands-On project on organism locomotion will explore stability and performance in organisms as they climb a track at angles ranging from horizontal to vertical. The project's goal will be to measure net and single limb forces as a function of track angle. The tracks will be coated with a monolayer of glass beads to provide mechanical rigidity to the substrate; this allows claws and frictional pads to engage to make good adhesive and frictional contact. Forces will be measured during locomotion of insects, spiders, and lizards using three-axis force platforms while simultaneously measuring kinematics using 1000 frame/s digital imaging. The force data will be analyzed in MATLAB together with custom tracking software. Simple dynamical models that capture the observed dynamics will be constructed and analyzed. Also, the animals will be perturbed with, for example, puffs of air, during locomotor tasks, and the recovery of stability will be compared to predictions from the models.

8. From Single Cells to Groups: Exploring Cell Response to Stimuli

Dr. Erin C. Rericha (Burroughs Wellcome Fellow, University of Maryland and the National Institutes for Health), Dr. Woodrow Shew (National Institutes of Health), and Dr. Jiri Borecky (UFABC)

The ability of cells to move towards environmental cues is a critical process allowing the immune system to chase down intruders and to remodel tissues during embryo development. Cancerous cells can co-opt these processes leading to spreading of tumors. Whether cells move as individuals or in groups, directed migration requires coordination between a cell's motility machinery and its sense of direction.

The social amoeba *Dictyostelium discoidum* is well suited for exploring single cell and group migration. Under optimal nutrient conditions, *Dictyostelium* exists as a single-celled organism that hunts bacteria by migrating up a chemical gradient of a bacterial byproduct, folic acid. A prolonged shortage of bacteria forces solitary cells to secrete, migrate towards, and relay the chemical signal cAMP, allowing solitary cells to merge into tight aggregates that mature into a multicellular slug. The slug moves toward heat and light, searching out optimal conditions for eventual spore dispersal. Using simple microfluidic devices and light chambers, participants will monitor how each Dictyostelium stage responds to changes in external stimuli. Using particle tracking techniques in MATLAB applied to image sequences, they will extract the migration speed, directionality and turning response for each of the conditions explored. The results will be compared with predictions from models of cell migration and directional sensing.

9. Complex Fluids and Brownian Motion

Professor Arjun Yodh and Peter Yunker (University of Pennsylvania), Professor Piotr Habdas (Saint Joseph's University, Philadelphia), and Dr. Dimas Betioli Ribeiro (UFABC)

Why does mayonnaise act like both a liquid and a solid? What causes soap foam to flow differently from toothpaste? Such questions are at the heart of the study of complex fluids -- materials with both fluid and solid properties. The answers to the questions posed relate the mesoscopic structure of a complex material to its macroscopic properties (such as its viscoelastic modulus).

Macroscopic Properties of Complex Fluids. Some simple properties of complex fluids will be examined using a microscope and simple instrumentation to determine flow properties. For example, shear-thickening fluids have a low viscosity when slowly stirred, but can act like solid materials if stirred quickly. Yield stress fluids stir quite easily, yet can support a finite amount of weight as if they were solids.

Brownian Motion. In 1827 botanist Robert Brown observed that micron-sized particles suspended in a fluid undergo random motion. This "Brownian motion" leads to diffusion. In 1905 Einstein derived an expression relating the diffusion coefficient characterizing Brownian motion to particle size, the absolute temperature, and viscosity. This project will examine the dependence of Brownian motion on these parameters. Participants will be introduced to particle-tracking software (available free on the web) to track the particle motion measure and deduce the diffusion constant. Further, quite different types of motion will be observed for particles in different complex fluids.

10. Nonlinear Dynamics of Coupled Nonlinear Electronic Circuits

Dr. A. Sen and Dr. Mitesh Patel (Institute for Plasma Research, Gandhinagar, India),
Dr. Syamal Dana (Indian Institute of Chemical Biology, Kolkata), and
Dr. Rodrigo Reinas (UFABC)

The dynamics of single and coupled nonlinear electronic circuits will be explored through both simulation 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 MATLAB. Synchronization and antiphase oscillations will be studied using coupled Chua oscillators, both with and without time delay. New dynamical states will be identified and studied as a function of coupling strength and time delay.

11. Mathematical Modeling and Data Analysis Using MATLAB

Dramatic advances in computing power now enable *every* scientist to include computational modeling in his or her toolkit. The speed of personal computers now matches that of some of the fastest supercomputers from 15 years ago. Further, advances in software make computational science possible without advanced training in programming or a large investment of the researcher’s time.

We will focus on a platform for computational modeling based on MATLAB, a commercial software package that has become ubiquitous in science and engineering. (Alternatively, participants can use the free ***Scilab*** software that is very similar to MATLAB, see www.scilab.org) MATLAB has many features that allow one to develop new simulations that are several times shorter than their counterparts written in traditional languages such as C or FORTRAN. Further, in MATLAB it becomes simple to integrate dynamic data visualization directly into models.

The development of computational skills using MATLAB will be a crucial part of the Hands-On Research School. Participants will learn how to develop models to interpret the hands-on experiments, and how to analyze both laboratory data and numerical results from models. Computational sessions will include introductory topics and problems that can be solved with short programs.

Three different modeling sessions are offered:

(11a) ***Introduction to MATLAB*** [first 4 days], *Professor Brian D. Storey (Olin College of Engineering), David Boy (U California Santa Barbara), Dr. Ziya Kalay (University of New Mexico), and Dr. Andre Fonseca (UFABC)*

This session will introduce the basic MATLAB environment and MATLAB commands. This session is designed for participants with little experience in programming. In addition to basic techniques for modeling, we will introduce methods for using MATLAB to connect computers to hardware for data acquisition and control. We will write short programs that can control simple thermal and electro-mechanical systems through hardware, simulate their physics, and compare the experimental data to simulation.

(11b) ***Nonlinear systems*** [6 sessions, beginning Friday]***,*** *Professor Brian D. Storey (Olin College of Engineering), David Boy (U California Santa Barbara), Dr. Ziya Kalay (University of New Mexico), and Dr. Andre Fonseca (UFABC)*

This session will examine the dynamics of ordinary differential equation models and the stability of fluid flows and other systems described by partial differential equations: Built-in solvers for ordinary differential equations and boundary value problems, as well as simple graphical output, make MATLAB a useful tool for understanding nonlinear systems. Participants will learn to write short scripts to solve classic problems of nonlinear dynamics such as the Lorenz equations. Methods for solving boundary value problems will also be introduced. Participants will apply these methods to problems of linear stability in hydrodynamics, but the ideas presented have wider applicability. This session is designed for participants with some basic experience in programming, but not necessarily prior experience with MATLAB.

(11c) ***Complex Networks,*** *Professor Michelle Girvan, Kimberly Glass, and Karl Schmitt (University of Maryland), and Dr. Andre Fonseca (UFABC)*

Participants will simulate and analyze systems for which the pattern of connectivity between interacting elements is crucial. They will examine social networks, systems of coupled oscillators, biological networks, disease networks, and technological networks, and they will explore these complex networks as the structure of the network is varied.

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