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# Advancing Access to Cutting-Edge Tabletop Science

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## Abstract

Hands-On Research in Complex Systems Schools provide an example of how graduate students and young faculty working in resource-constrained environments can apply key mindsets and methods of tabletop experiments to problems at the frontiers of science. Each day during the Schools' two-week program, participants work in small groups with experienced tabletop scientists in interactive laboratories on topics drawn from diverse disciplines in science and technology. Using modern low-cost tools, participants run experiments and perform associated data analysis together with mathematical and computational modeling. Participants also engage in other scientific professional activities; in particular, they learn best practices for communicating their results visually, orally, and in writing. In this way, the Hands-On Schools foster the development of scientific leaders in low- and middle-income countries.

## 1. INTRODUCTION

Tabletop experiments have a long and storied history in fluid dynamics: Henri Bénard's elegant observations of convection cells in a thin fluid layer heated from below (Bénard 1900) and G.I. Taylor's analysis and pioneering experiments on instability onset in flow between rotating cylinders (Taylor 1923) are two of many outstanding examples. In fluid dynamics and other disciplines (e.g., soft matter physics, chemistry, and the physics of living systems), tabletop scientific studies have yielded countless discoveries and spawned entirely new lines of research. The pace of breakthroughs has accelerated in recent years, thanks in part to the consumer-driven microelectronics revolution, which has yielded novel tools for control, sensing, data acquisition, data storage, and computing that are powerful and often available at very low cost. As a consequence, many investigators across the globe can afford advanced scientific tools, including sensitive image sensors with broad dynamic range and megapixel resolution, terabyte-scale data storage devices, and laptop/mobile devices with gigaflop performance. Thus, scientists throughout the world can develop cutting-edge research programs, open up educational opportunities for new generations, and develop imaginative tabletop experiments to address critical problems in their local environments.

Beginning in 2008, a series of Hands-On Research in Complex Systems Schools was created to help unlock the potential for widespread top-notch tabletop science. A list of Hands-On Schools is given in **Table 1**. Executing excellent tabletop scientific research requires more than just access to suitable tools and instruments; shared mindsets and methodologies for effective tabletop science are essential and are learned in the context of communities of practice (Wenger-Trayner & Wenger-Trayner 2015). Thus, the Hands-On Schools engage scientists and engineers from low- and middle-income countries (LMICs) in an intensive experiential introduction to tabletop tools and practices in partnership with senior scientists with demonstrated success in cutting-edge tabletop experimentation. Participants develop an understanding of physical phenomena by making measurements with accessible instruments, varying parameters, analyzing data, and drawing their own conclusions about their observations. Exposure to state-of-the-art research is not the primary aim; instead, the Hands-On Schools' central goals are to empower scientists all over the world to develop cutting-edge research programs with low-cost instrumentation, to open up educational opportunities for a new generation, and to address critical problems in their local environment using imaginative and insightful tabletop experiments. We believe locally driven science can create solutions and technological development in unique ways. For example, investing in the local

**Table 1 List of Hands-On Research in Complex Systems Schools**

| School | Location | Dates |
|---|---|---|
| HOS08 | Institute for Plasma Research, Gandhinagar, India | January 6–18, 2008 |
| HOS09 | Federal University of ABC, Santo André, Brazil | July 26–August 6, 2009 |
| HOS10 | University of Buea, Buea, Cameroon | August 2–13, 2010 |
| HOS12 | Shanghai Jiao Tong University, Shanghai, China | July 17–29, 2012 |
| HOS13 | International Centre for Theoretical Physics, Trieste, Italy | July 1–12, 2013 |
| HOS14 | International Centre for Theoretical Physics, Trieste, Italy | June 30–July 11, 2014 |
| HOS15 | International Centre for Theoretical Physics, Trieste, Italy | June 29–July 10, 2015 |
| HOS16 | International Centre for Theoretical Physics, Trieste, Italy | July 18–29, 2016 |
| HOS17 | International Centre for Theoretical Physics, Trieste, Italy | July 30–August 11, 2017 |
| HOS18 | International Centre for Theoretical Physics, Trieste, Italy | July 16–27, 2018 |
| HOS19 | International Centre for Theoretical Physics, Trieste, Italy | July 21–August 2, 2019 |

ownership of research questions is likely to deliver substantial societal and technological benefits that differ significantly from those of investing comparable resources into big-science initiatives.

The remainder of the paper is organized as follows: In Section 2, the general structure of the Schools is briefly outlined. Section 3 describes the heart of the program: the hands-on laboratories. Section 4 covers selected professional development activities offered at the Hands-On School, which are also critically important for career advancement. Section 5 provides some data on the impact of the Hands-On Schools, and Section 6 discusses the outlook and lessons learned for future Hands-On Schools.

## 2. STRUCTURE OF HANDS-ON SCHOOLS

Most participants in the Hands-On Schools come from LMICs. For the Schools based at the International Centre for Theoretical Physics (ICTP) in Trieste, Italy, there were typically 50–75 participants per summer, and each summer's School typically received hundreds of applicants from around the globe. In contrast, the first four Schools, HOS08, HOS09, HOS10 and HOS12, were located in different regions of the world, with the majority of these Schools' participants coming from LMICs in South Asia, Latin America, sub-Saharan Africa, and East Asia, respectively. In all the Schools, most selected participants were early-career graduate students, postdoctoral scholars, and faculty in engineering, mathematics, and the physical, chemical, and biological sciences. On average, approximately one-third of the participants were women.

Over the years, the Schools' format has been optimized. Recent programs operate for 10 working days with about 10 School faculty members, each aided by a graduate student or postdoc, often from a given faculty member's research group. Hands-on laboratory sessions are the core of all the Schools. In the morning, participants rotate into one of 10–12 half-day lab sessions featuring either intensive experimental or computational modeling activities. In the afternoon, activities include professional development tutorials, advanced laboratories that extend the core hands-on experiences, and presentations of participants' work in oral and poster sessions. This combination of experiences is key to the success of the program.

## 3. HANDS-ON LABORATORIES

### 3.1. General Considerations

The hands-on laboratories' primary purpose is to empower participants with the ability to incorporate tabletop experiments and methods into their research and teaching laboratories. The Hands-On Schools' laboratories emphasize mindsets, knowledge, and skills that allow important scientific questions, drawn from real-world problems, to be addressed in tabletop experiments conducted at a leading-edge level in resource-constrained environments by using low-cost technologies that were originally developed for other purposes (e.g., communication, social media, personal computing).

Each hands-on laboratory session engages participants in discipline-specific activities. Selected tabletop experiments drawn from fluid dynamics (Section 3.2), granular media/soft condensed matter (Section 3.3), and the physics of living systems (Section 3.4) are described below. Hands-on experience with computational modeling (Section 3.5) in support of tabletop experiments is also described. The **Supplemental Appendix** gives additional information on these experiments and describes additional tabletop experiments and techniques from other disciplines.

Supplemental Material >

### 3.2. Fluid Dynamics

Tabletop studies of fluid flows play a key role in advancing understanding of and developing solutions to numerous problems encountered all over the world. For example, adverse impacts of human activities on the Earth's environment such as climate change and pollutant transport in the oceans involve fluid behaviors that are both fundamentally important and incompletely understood (Dauxois et al. 2021). In conjunction with field observations and analytical/numerical models, tabletop experiments can also provide the scientific foundations for engineering new and sustainable approaches for mitigating negative anthropogenic effects and improving human well-being.

A hands-on laboratory using flow between concentric rotating cylinders (Taylor–Couette flow) has been used to introduce Hands-On School participants to fundamental aspects of instability, an important feature in many real-world fluid flows. The laboratory familiarizes participants not only with historically important advances [experimental validation of both hydrodynamic stability theory and the no-slip condition at solid boundaries for viscous flows (Taylor 1923)] but also with powerful approaches for understanding and characterizing instabilities that arise in modern settings (e.g., tipping points in the Earth's climate). In this subsection, the Hands-On School's Taylor–Couette flow laboratory is described in brief; more details and other examples of the School's fluids laboratories (e.g., studies of 2D turbulence, microfluidics, surface tension–dominated flows), as well as tutorials on fluid dynamics modeling, can be found in the **Supplemental Appendix**.

Supplemental Material >



This laboratory provides knowledge about accessible approaches to constructing a concentric rotating cylinder apparatus, instrumenting the apparatus for high-resolution control and measurements, and analyzing data acquired from the experiment. Although a concentric cylinder apparatus requires precision alignment of the inner and outer cylinders, it can be constructed using low-cost acrylic tubing (for detailed plans see Borrero-Echeverry 2018). In the laboratory, the inner cylinder is driven with an inexpensive NEMA23 stepper motor, although any direct current motor with precision control, such as a servo-motor, would also be appropriate. The inner cylinder rotation frequency, which determines changes to the flow's control parameter (the Reynolds number $R$), is precisely controlled using an inexpensive microcontroller programmed in Python, which is open source. The spatial structure of the flow is rendered visible by adding microscopic flat flakes extracted from shaving cream to the working fluid (water), as described by Borrero-Echeverry et al. (2018). The visualized flow is illuminated using inexpensive LED (light-emitting diode) flashlights, and videos of the flow are recorded using inexpensive USB webcams and analyzed using custom scripts written in MATLAB. Participants determine the onset of fluid instability, analyze spectra of flows above instability onset, and represent flow complexity using phase space portraits. Each of these activities is described below.

#### 3.2.1. Activity: identifying the onset of an instability.

Taylor vortex flow is a classic example of a fluid that undergoes a forward or pitchfork bifurcation from the base state. Participants determine the onset of instability by changing $f_{\mathrm{cyl}}$, the rotation frequency of the inner cylinder, in a systematic fashion, while the outer cylinder is held at rest. For small $f_{\mathrm{cyl}}$, only the fluid's azimuthal velocity component is nonzero, and it is given by $v_\theta(r) = Ar + B/r$. Applying the fluid no-slip boundary condition at the inner and outer cylinder walls gives, respectively, $v_\theta(r_{\mathrm{i}}) = 2\pi f_{\mathrm{cyl}} r_{\mathrm{i}}$ and $v_\theta(r_{\mathrm{o}}) = 0$, which yield $A = -2\pi f_{\mathrm{cyl}} r_{\mathrm{i}}^2/(r_{\mathrm{o}}^2 - r_{\mathrm{i}}^2)$ and $B = -A{r_{\mathrm{o}}}^2$ (Taylor 1923). An analysis and experiment by Taylor (1923) showed that when $f_{\mathrm{cyl}}$ is increased, a critical rotation frequency $f_{\mathrm{c}}$ and Reynolds number $R_{\mathrm{c}} = 2\pi f_{\mathrm{c}} r_{\mathrm{i}}(r_{\mathrm{o}} - r_{\mathrm{i}})$ is reached where the axial invariance of the flow is broken. Toroidal (donut-shaped) vortices form, encircling the inner cylinder, as shown in **Figure 1*a***.

Participants are shown the Taylor vortex flow in **Figure 1*a*** and are asked to design a method to determine the onset of instability. The value of $f_{\mathrm{c}}$ can be computed from the known critical Reynolds number for Taylor vortex flow, but the learning goal for the participants is to understand the most efficient method of determining the threshold of instability in any type of system

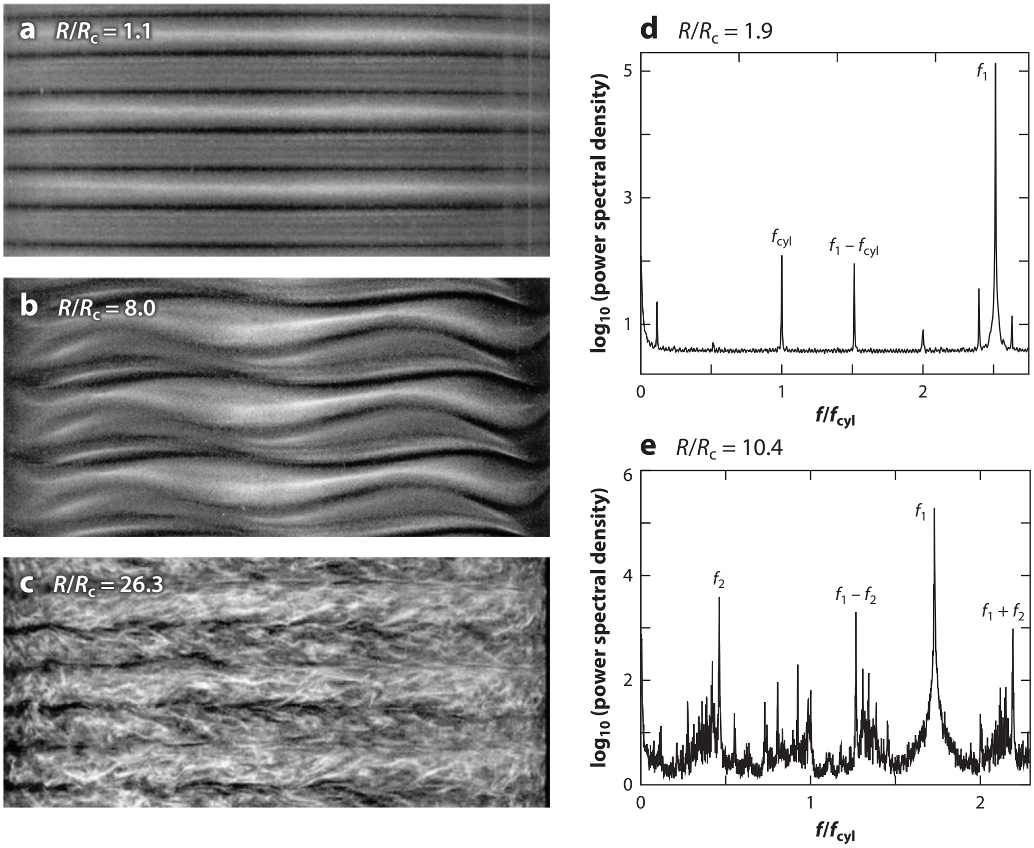


**Figure 1**

(*a*) The time-independent pattern of vortices that form at the first instability of fluid flow between concentric cylinders with the inner cylinder rotating and the outer cylinder at rest. The horizontal lines are boundaries between adjacent toroidal vortices that encircle the inner cylinder and are stacked along the cylinder axis. The Reynolds number $R = 2\pi f_{\mathrm{cyl}} r_{\mathrm{i}}(r_{\mathrm{o}} - r_{\mathrm{i}})$ is a measure of the system's distance from thermodynamic equilibrium. (*b*) When $R$ is increased sufficiently far above $R_{\mathrm{c}}$, a second instability is reached where these azimuthal traveling waves appear on the vortices. (*c*) At much larger $R$ the flow becomes temporally nonperiodic and spatially disordered. (*d*) The power spectrum for flow with azimuthal traveling waves, as shown in panel *b*. The spectrum contains a single fundamental component $f_1$, the frequency of the waves passing the camera. The spectrum also contains harmonics of $f_1$ and another spectral component, $f_{\mathrm{cyl}}$, which appears because the cylinder is not perfectly circular. (*e*) With increasing $R$, another instability occurs, as shown in panel *b*, where a second fundamental frequency $f_2$ appears in the spectrum. The spectrum also then contains lower-amplitude spectral peaks that are linear combinations and aliased harmonics of $f_1, f_2$, and $f_{\mathrm{cyl}}$.

driven away from thermodynamic equilibrium. The participants' collective choice is typically to increase the cylinder rotation rate in small increments. However, using incremental changes in $f_{\mathrm{cyl}}$ takes an unnecessarily long time to find the onset of instability at $f_{\mathrm{cyl}} = f_{\mathrm{c}}$ because an increasing amount of time is necessary to decide whether the system's state is unstable as the transition point is approached; this phenomenon is called critical slowing down. Participants learn that for any nonequilibrium system that makes a continuous (nonhysteretic) transition, the most efficient method uses a binary search: The instability is bracketed between upper and lower bounds, and then the best estimate for the transition is halfway between the bounds. Participants are often able to determine $f_{\mathrm{c}}$ with an uncertainty less than one percent in only a half-hour using a binary search. They then compare their critical Reynolds number to theory.

**3.2.2. Activity: spectral analysis.** When $f_{cyl}$ is increased above $f_c$, a second instability is reached where azimuthal traveling waves appear on the boundaries between adjacent vortices, as illustrated in **Figure 1*b***. Such a transition from a time-independent state to a time-periodic state (a Hopf bifurcation) occurs in many systems at a precise value of the control parameter that characterizes the system's distance away from equilibrium. Participants analyze the dynamics of the flow by recording videos at different rotation rates and determining the temporal frequencies in the flow pattern from pixel data using a MATLAB spectral analysis program.

Spectral analysis is an important and common tool in science, but it is new to many Hands-On School participants. **Figure 1** shows the types of flow states analyzed by Hands-On School participants. The power spectral density of the time-varying intensity from a small region in the video image of the flow pattern shown in **Figure 1*b*** yields a spectrum with a single fundamental frequency component, as **Figure 1*d*** illustrates. Spectra obtained from videos with a higher video frame rate contain many harmonics of the fundamental frequency $f_1$ but no other spectral components. Participants learn how the Nyquist theorem and aliased frequencies influence an appropriate choice for camera frame rate and the length of the video, how to distinguish harmonics from additional fundamental frequencies, and how averaging over thousands of pixels reduces noise in the data, thus revealing sharp spectral peaks even though an analysis of data from a single pixel in the video might not reveal any characteristic frequencies.

Participants also visually examine videos to determine the integer number of wavelengths wrapping around the cylinder. This analysis reveals, for example, that the spectrum in **Figure 1*d*** is for a flow with four waves around the annulus. Thus, the spectral component $f_1/f_{cyl} \approx 5/2$ arises from five waves rotating at a frequency that is about 1/2 of the cylinder rotation rate.

Participants then analyze videos obtained for higher cylinder rotation rates, and they find that another well-defined instability is reached where the time-varying intensity now contains two fundamental frequencies, $f_1$ and $f_2$, as illustrated in **Figure 1*e***. Power spectra obtained at much higher video frame rates reveal additional peaks in the spectra; the additional peaks are all at multiples, sums, and differences of $f_1$ and $f_2$. Thus, the dynamics of the fluid flow is completely characterized by two fundamental frequency components. Interpreting spectra that have aliasing and frequency mixing is another important learning goal for participants in the session.

The session concludes with study of the consequences of a further increase in the inner cylinder rotation rate: A fourth instability is reached where the flow becomes nonperiodic, as in **Figure 1*c***. The power spectrum for the nonperiodic flow still contains the components $f_1$ and $f_2$ but also contains intense broadband noise that exhibits exponential decay (i.e., a straight line on a log-linear plot). The participants learn that the measurement of the transition to a noisy signal in the concentric cylinder system provided the first experimental evidence of the onset of chaos in a dynamical system (Gollub & Swinney 1975).

**3.2.3. Activity: identifying and characterizing chaos with phase space portraits.** Phase space portraits are now a widely used tool for analyzing chaotic behavior in diverse systems, but phase portraits are also new to most Hands-On School participants. Multidimensional phase space portraits can be constructed from a time series record of any temporally varying quantity; here, the quantity is the intensity of a small region in video images, $I(t_j)$, with $t_j = j\Delta t$ and $j = 1, \ldots, N$, where $N$ is large (e.g., $N = 2^{12}$). The time interval $\Delta t$ is chosen to be small (e.g., 1% of the cylinder rotation period). Then a phase space portrait characterizing the system dynamics is constructed from the motion of a point in an $m$-dimensional space, $(I(t_j), I(t_j + T), .., I(t_j + (m-1)T))$, where $T$ is a time delay, which is typically chosen to be about 1/3 of the cylinder period. More precisely, an information-theoretic method can be used to select an optimum time delay $T$ (Fraser & Swinney 1986). According to mathematical embedding theorems, the phase space attractor constructed using the time-delay method will have the same properties, such as fractal dimension, as those of a phase space attractor constructed from other spatial points in the fluid flow (this is not obvious!). Attractors constructed for a flow such as in **Figure 1*c*** are termed chaotic or strange. The analysis of dynamics using time series data to construct phase space portraits has been applied to many systems in science and engineering. The Hands-On School participants use their video data to construct phase portraits for flow states such as those shown in **Figure 1**. A systematic procedure for constructing a phase portrait from time series data is described by Roux et al. (1983), and a procedure for analyzing chaotic (strange) attractors is described by Wolf et al. (1985).

## 3.3. Soft and Granular Matter

Tabletop experiments are well suited to explore soft matter systems, which are composed of building blocks larger than an atom but smaller than the system size (Nagel 2017). The variety of soft materials is vast, including foams, colloids, emulsions, polymers, amphiphiles, liquid crystals, and granular matter. Consequently, soft matter physics is ubiquitous in both nature (e.g., desert sand dune evolution, ocean sedimentation, planetary ring formation, cellular tissue growth) and technology (e.g., numerous applications in the food processing, energy production, chemical, pharmaceutical, and construction industries). The large dimensions and, correspondingly, slow time evolution of basic units (relative to atomic length scales and timescales) enable the dynamics of many soft matter systems to be quantitatively explored in cleverly designed, inexpensive tabletop studies.

We describe here two settings explored by participants in the Hands-On School's laboratories: granular matter and colloids composed of Brownian or active (self-propelled) particles. Experiments involving granular matter prepare participants to engage with scientific questions relevant to societal applications involving highly dissipative matter, including soil remediation, mining and resource extraction, erosion, and water purification (Nagel 2017). The development of expertise in colloidal experimental methods allows participants to explore the basic science behind a variety of consumer products, as well as the soft matter basis of life in a host of biological systems. More details and other examples of the School's soft matter laboratories (e.g., foam relaxation, locomotion in complex environments, origami metamaterials, surface tension effects in liquids) can be found in the **Supplemental Appendix**.

Supplemental Material >

The Hands-On School laboratories for colloidal and granular systems communicate to participants powerful digital imaging measurement and analysis methods, together with simple techniques for illuminating and controlling experimental setups. In both colloidal and granular studies, experiments are imaged using inexpensive digital cameras. Current cellphone cameras often feature slow motion image capture at frame rates approaching 1 kHz and are well suited for use in experiments (Lai et al. 2017). A series of low-cost microscopes were built for the colloidal experiments: Initially microscopes were built using lenses and metal clamps, while in later Schools open-source hardware projects were featured, such as the $100 3D-printed OpenFlexure Microscope (OpenFlexure 2022). LEDs provide illumination for visualization and imaging of soft matter experiments. For oscillating granular flows, low-cost speakers combined with integrated audio controllers found in laptops and computers provide vibration combined with field-programmable gate arrays (FPGAs) and Arduino-like microcontrollers to create synchronized stroboscopic LED illumination. Custom software codes written in both Python and MATLAB are used for image acquisition and analysis, as well as for experimental control.

**3.3.1. Activity: dynamic differential microscopy of colloidal particle motion.** In this laboratory, participants learn to quantitatively characterize the diffusive motion of particles in colloids. At times, colloidal particles undergo normal diffusion; for example, the Brownian motion of thermally driven micrometer-scale spherical particles in Newtonian fluids is well described by the Stokes–Einstein relation, $D = k_B T/(6\pi \eta r)$, which links the diffusion coefficient $D$ to the Boltzmann constant $k_B$, the temperature $T$, the viscosity $\eta$, and the radius of the particle $r$. However, under real-world conditions for many colloids, the rich interplay of particle and solvent properties can give rise to particle motions that are anomalously diffusive—often subdiffusive in a polymer or gel matrix, or superdiffusive if there is active propulsion or if the particles are being advected by fluid flows. Measurements of such motions are critical for elucidating fundamental physical mechanisms.

Participants learn a powerful optical technique for particle motion analysis: dynamic differential microscopy (DDM) (Cerbino & Trappe 2008, Giavazzi et al. 2008, Cerbino & Cicuta 2017). Under ideal circumstances, tracking particles as a function of time to determine mean-square displacement provides a direct measure of diffusive motion; however, under real-world conditions (e.g., high particle density, challenging imaging conditions, poorly defined particle boundaries), this direct approach often fails. DDM provides an alternative approach. In DDM, two particle images captured at different times separated by a time interval $\tau$ are subtracted and the corresponding 2D spatial Fourier transform is computed. By repeating this process for subtracted images for a range of $\tau$, Hands-On School participants can determine an intermediate scattering function (Giavazzi et al. 2008) that robustly characterizes particle motion (**Figure 2**).

Participants in the laboratory study samples of micrometer-scale (polystyrene) spherical particles in water that undergo either Brownian motion or sedimentation; in some Schools, participants also examine an active-matter colloid containing the single-cell swimming alga *Chlamydomonas reinhardtii*. For all experiments, participants construct sample chambers using microscope slides. For the Brownian motion and sedimentation studies, participants prepare various colloidal dilutions and pipette solutions into the sample chambers; for studies with motile algae, laboratory time constraints require advance preparation of the samples and maintenance of the algae stock.

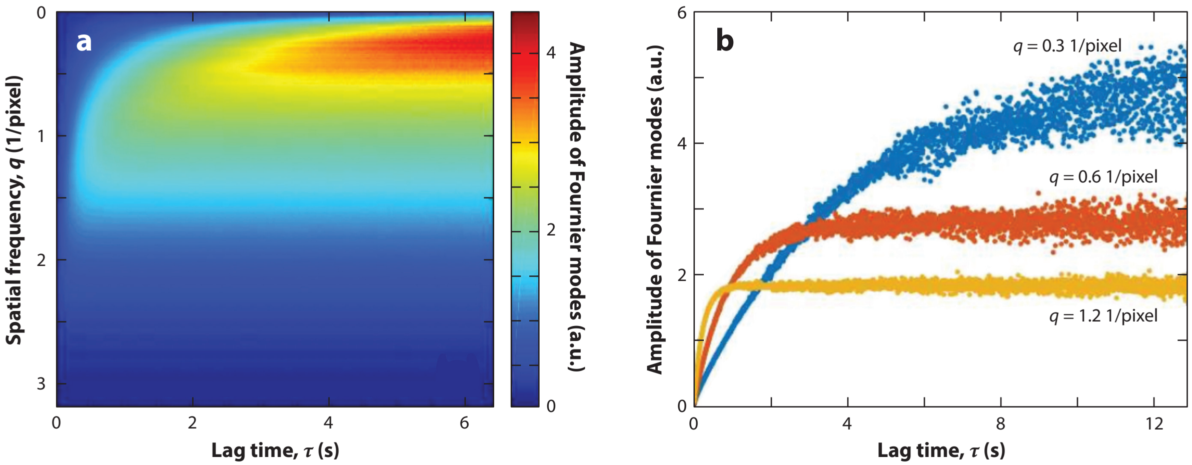


**Figure 2**

Dynamic differential microscopy analysis of images from videomicroscopy enables classification of motion and identification of dynamical parameters, even when very basic optics and mechanics are used. (*a*) From fast Fourier transform of image differences, averaged for equal lag times and azimuth, a sample of colloidal particles will display a signal that grows with lag time to some saturation value and peaks at some finite spatial frequency $q$ that depends on the optics. (*b*) These data are typically investigated as a function of lag time for some values of spatial frequency. The data (in arbitrary units) can be fitted to extract a timescale $\tau_q$, where the $q$-dependence describes the type of motion (e.g., subdiffusive, diffusive, ballistic); moreover, in the cases of diffusive and ballistic motion, the prefactor quantifies precisely the diffusion coefficient or the velocity, respectively.

Participants learn methods of imaging and image analysis together with the DDM approach. A group of usually four participants work together to operate a microscope with a digital camera and to master techniques of microscope control, sample illumination, and acquisition of digital movies, which are typically 10–20 s in length. Prewritten, commented MATLAB scripts for DDM analysis are provided and discussed in a step-by-step manner. (The MATLAB scripts can be readily ported to open-source programming languages like Python.) An experimental run (from image acquisition to DDM analysis) takes several minutes, thereby enabling participants to explore parameter dependencies in a series of samples during the course of one laboratory session.

Participants gain experience quantifying particle motion under a range of conditions. For Brownian motion of spherical colloids, the intermediate scattering function is expected to exhibit an exponential behavior dictated by the particle self-diffusion $D$. Participants determine $D$ from curve fitting to intermediate scattering functions measured for a range of particle diameters and compare the measurements of $D$ to predictions from the Stokes–Einstein relation. By contrast, sedimenting particles and swimming algae exhibit directed (ballistic) motion that is distinct from normal diffusion. Participants analyze intermediate scattering functions obtained from movies of algae swimmers and determine the average swimming velocity. In a similar vein, participants characterize the ballistic motion of Brownian spherical particles that are not density matched with the colloid solvent by tilting the sample chamber and determining from DDM analysis the corresponding sedimentation velocity.

**3.3.2. Activity: granular gases.** In the granular gases laboratory, participants examine the granular analog of the ideal gas law. Granular flows are highly dissipative and far from thermal equilibrium; nevertheless, concepts from thermodynamics can be used provided that the external forcing of the flows is sufficiently strong. For example, by applying oscillations at frequency $f$ with an amplitude $A$ that is sufficiently large, the average particle kinetic energy behaves like a granular temperature. As the amplitude $A$ and the granular temperature increases, the system shows several interesting thermodynamic-like behaviors, including a first-order phase transition, shock waves, and quenching and annealing cycles.

Participants assemble a 2D container with a single layer of spherical particles (stainless steel ball bearings) of diameter $D = 3.175$ mm. The container is made from parts that are readily available even in resource-constrained environments. Specifically, the glass for the front and back plates of the cell is commonly used for picture frames. The side walls and plunger could be made from wood or plastic strips. The container, oriented vertically, is $20D$ high, $17.5D$ wide, and filled with a sufficient number of particles to produce two to six hexagonally packed rows. A freely floating weight in contact with the particles at the top provides constant pressure while allowing the volume containing the particles to fluctuate when the particles are in motion. This granular system is heated by the sinusoidal motion of the container's bottom boundary, which is mechanically connected to a loudspeaker driven by a computer audio output, with a specified $A$ and $f$ programmed by participants.

In a series of experimental runs, participants capture and analyze movies of particle motion to quantify the trajectories of each particle. In a given run, participants fix $f$ and capture a sequence of movies (at a frame rate of 420 Hz) as $A$ is increased and then decreased in small steps. Additional runs are performed similarly at different values of $f$. Participants write MATLAB codes to track each particle's location (to a subpixel accuracy of $D/1{,}000$) in every movie. From the particle tracking data, the participants extract time-dependent particle densities, velocities, and granular temperatures, as well as the system-averaged container volume and particle kinetic energy. The participants observe hysteretic phase transitions between crystalline and gaseous states as $A$ is increased and decreased. From these observations, participants compute the gas compressibility $\chi(A, f)$ and note that $\chi$ changes discontinuously as the system crystallizes. Additionally,

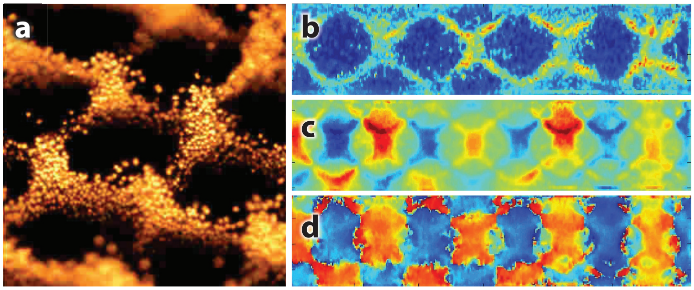


**Figure 3**

(*a*) Snapshot of vertically vibrated 165-µm bronze spheres showing one phase of a square pattern formed at low driving frequency. (*b*) Frame from Hands-On School participants' movie showing square patterns in a cell with aspect ratio $L/W = 4.5$. (*c*,*d*) Images of the time-independent amplitude (*c*) and phase (*d*) extracted from the movie in panel *b* by participants.

participants find in the gaseous phase (at fixed $f$), $\chi$ approaches zero (ideal gas limit) for large $A$, while van der Waals–like excluded volume effects are observed at low driving (just as in an atomic gas). Participants discover that for a wide range of $f$, $\chi(A, f)$ collapses when plotted as a function of $Af$, suggesting that the granular temperature depends mostly on the velocity of the driving plate.

**3.3.3. Activity: patterns in vibrated granular layers.** In another laboratory, participants explore pattern formation in vertically vibrated thin granular layers; experimental study of these behaviors tests continuum theories of granular flows. Participants place a 1- to 4-mm layer of 0.165-mm-diameter bronze spherical particles in a rectangular dish of size 101.6 mm × 25.4 mm. The dish of particles is vertically vibrated by a mechanical connection with a loudspeaker driven by participant-programmed sinusoidal waveforms with a specified amplitude $A$ and frequency $f$. Participants illuminate the vertically vibrated particle layers with LEDs shining at a low incidence angle and visualize vibrated particle patterns in two ways. In some experiments, an FPGA, configured as a phase-locked loop, is used to strobe the LEDs synchronously at $f/2$, thereby enabling participants to directly observe the particle patterns at any phase of oscillation. In other experiments, the LEDs are always on while movies of particle patterns are captured at a frame rate of 420 Hz (**Figure 3*a***).

The participants observe a rich variety of granular patterns (**Figure 3**) including squares, stripes, hexagons, kinks, phase domains, and solitary structures (Dinkelacker et al. 1987; Thomas et al. 1989; Melo et al. 1994, 1995; Umbanhowar et al. 1996; Bizon et al. 1998; Moon et al. 2002). They find that for a broad amplitude range, the observed patterns are subharmonic, oscillating at a frequency of $f/2$, and that the type of pattern observed is determined by the nondimensional driving amplitude $\Gamma = A(2\pi f)^2/g$ and frequency $f^* = f/\sqrt{gH}$ in terms of $A, f$, the depth of the layer $H$, and the acceleration of gravity $g$. Participants quantify pattern behaviors using custom-written MATLAB scripts to obtain time-independent complex amplitudes $\mathcal{A}(\mathbf{x})$ from movie snapshots of the form $M(\mathbf{x}, t) = \Re[\mathcal{A}(\mathbf{x})\exp(2\pi i f_{\mathrm{d}} t)]$ using demodulation at frequency $f_{\mathrm{d}}$. By varying $f_{\mathrm{d}}$, participants can map out the full phase behavior of the pattern. For the range of $\Gamma$ and $f^*$ studied, there is only one significant $\mathcal{A}(\mathbf{x})$ for $f_{\mathrm{d}} = f/2$. The amplitude $|\mathcal{A}(\mathbf{x})|$ and phase $\mathrm{Arg}(\mathcal{A}(\mathbf{x}))$ are shown in **Figure 3*c*,*d***.

## 3.4. Physics of Living Systems

Physical approaches (both conceptual and technological) can be used to yield new understanding of biology and uncover new physical concepts. Bacteria are studied in several laboratories at

Hands-On Schools. In this subsection, participant activities to quantify bacterial growth inhibition by antimicrobial candidates and to examine the physics of bacterial motility are outlined; more details and other examples of the Schools' physics of living systems laboratories are in the **Supplemental Appendix**.

Supplemental Material >

The Hands-On School laboratories familiarize participants with techniques and limitations of tabletop bacterial studies under resource-constrained environments. Data acquisition in the bacterial labs emphasizes visual observations and, for the bacterial motility studies, low-cost digital videomicroscopy similar to that employed in other labs (Section 3.3). The Schools' lack of dedicated facilities for biological research approximates the circumstances that some participants experience at their home institutions. In this setting, participants work only with nonpathogenic organisms (Biosafety Level 1) that are relatively insensitive to temperature changes. Nevertheless, participants practice good sample handling methods with proper sterile culture technique. For example, in the bacterial motility studies, participants employ good practices to minimize contamination when pipetting bacterial samples for microscopy; additionally, in the antimicrobial studies, any participant observed making mistakes in sterile techniques is required to redo the steps and provide a discussion of what the mistake was, why it mattered, and how to do that step correctly. Moreover, at the end of the laboratories, participants sterilize all biological samples with bleach and ethanol before safe disposal (see **Supplemental Appendix** for further details).



Due to time limitations and the lack of infrastructure at the Schools, prior to the start of the labs, faculty sterilize some laboratory materials (e.g., growth media) and grow the bacteria (for the motility studies); moreover, other materials (e.g., culture tubes, L-spreaders, paper disks) are purchased presterilized. With more time, participants could harness low-cost hardware for sterilization [e.g., pressure cooker–based autoclaves (Tao et al. 2012)], incubation, and agitation (Arumugam et al. 2021, Diep et al. 2021).

**3.4.1. Activity: antimicrobial efficacy and diffusion.** In one Hands-On School laboratory, participants use disk diffusion assays (Hudzicki 2009) to probe the inhibition of bacterial growth by antimicrobial agents. Three antimicrobial candidates are tested: ethanol, hydrogen peroxide, and eucalyptus oil, which are cheap, readily available, and do not require refrigeration. Participants spread five droplets (from a presterilized, disposable plastic dropper) of an overnight culture suspension of the bacterium *Escherichia coli* on sterile nutrient agar plates, place sterile paper disks on the inoculated plates, and place one drop of different candidate antimicrobial solutions on each disk. Participants then set aside the plates they prepared for incubation (for use by participants in the next day's lab) and examine bacterial growth on plates prepared 24 hours earlier by participants in the previous day's lab. Typically, after 24 hours of growth, there are lawns of bacteria on the plates; cleared regions around the disks indicate locations where bacteria were killed or their growth inhibited. The sizes of the cleared regions depend on properties of the specific candidate antimicrobial, including the amount applied, the diffusion constant, and the efficacy against the bacteria being tested [see **Figure 4*a*–*c*** and Bonev et al. (2008), Kaushik et al. (2015b), Edward (1970)].

Due to time constraints, the participant-prepared assays are suitable only for qualitative observations; for quantitative analysis, participants are provided example datasets that were previously collected. Participants and faculty discuss modeling the data using physical ideas of diffusion and curve-fitting with Microsoft Excel. Participants and faculty also discuss how the disk diffusion assay could be used for bio-prospecting for antimicrobial materials and to assess the efficacy of commercially purchased products (Freire-Moran et al. 2011, Höjgård 2012, Newman & Cragg 2020). Since most of the materials used in this experiment are prepared by Hands-On School

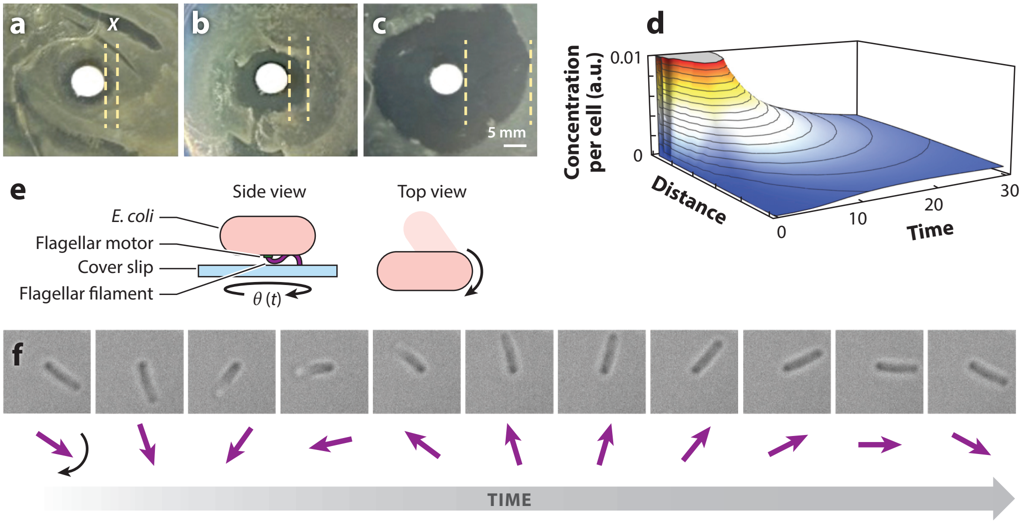


**Figure 4**

(*a–c*) Agar plates prepared by students at the Hands-On School with filter paper disks on which is applied (*a*) eucalyptus oil, (*b*) ethanol, or (*c*) hydrogen peroxide. After *Escherichia coli* bacteria have been allowed to grow overnight on the plates, bacteria-free regions called zones of inhibition are seen around the filter disks. The size of the zones of inhibition (*dashed lines*) is set by the distance from the filter paper disk that the antimicrobial factor reached when its per-cell concentration dropped below the growth-inhibiting threshold. Panels *a–c* adapted from Kaushik et al. (2015a); copyright 2015 the authors and distributed under a CC BY 4.0 license. (*d*) The concentration of antimicrobial per bacterial cell varies both as a function of distance from the disk and time, as the antimicrobial factor diffuses out and the bacterial population increases. Thus, the size of the region of inhibition (as in panels *a–c*) depends on the diffusion constant of the inhibitory factor, as well as on additional parameters that can be experimentally varied when more time is available. (*e*) An *E. coli* bacterial cell tethered to the surface of a microscope cover slip. The bacterial flagellar motor (*small green rectangle*; not to scale) is anchored to the cover slip surface by a bacterial flagellar filament (*purple*). Rotation of the motor then rotates the entire cell body. Ordinarily, about a half-dozen filaments are randomly distributed along the cell body, and the filaments form a bundle that propels the cell forward. (*f*) Data recorded by one of the participants; purple arrows indicate the rotational direction of the cell body driven by the anchored bacterial flagellar motor.

faculty, participants are provided with videos showing the preparation. The videos, along with a fuller description of this laboratory, have been provided by Kaushik et al. (2015a).

**3.4.2. Activity: bacterial motility.** In this laboratory, participants recreate a classic experiment that demonstrated bacteria like *E. coli* are motile because of a rotary nano-motor that drives a bundle of rotating filaments, which propel the cell forward (Silverman & Simon 1974). The experiment is visually engaging and the basis of many subsequent studies of motor structure and function (Block & Berg 1984, Berry & Berg 1997, Ajaev & Davis 1998, Walter et al. 2007, Naaz et al. 2021). The activity is divided in four parts: introduction, biological sample preparation, data collection, and discussion of data analysis. The participants examine a nonpathogenic *E. coli* strain that is genetically modified to ease the attachment of the motor to the surface.

In the introduction, participants and faculty survey all aspects of the experiment. The key elements of bacterial motility are discussed. The main experimental steps are then outlined. In particular, participants are directed to examine the main components of the digital microscope for the activity; faculty and participants discuss affordable methods for microscope construction and usage in teaching and research settings.

Next, participants prepare a bacterial sample for microscopy. They create a tunnel slide sample chamber using double-sided tape sandwiched between a microscope slide and cover slip (see

**Supplemental Appendix** for details) (Rosko et al. 2017). Participants then pipette a bacterial suspension into the tunnel slide. After a short time, the bacteria self-attach to the cover slip surface; the bacteria's rotary motor, so anchored, causes the entire bacterial cell to rotate (**Figure 4*e*,*f***). Participants view (after focusing the microscope) and record the cell rotation; this is the most visually engaging part of the experiment, and it generates excitement among the participants.

Supplemental Material >

Due to time constraints, participants do not analyze movies of cell rotation but discuss the analysis methods, which are subsequently demonstrated by laboratory faculty. The discussions highlight current research topics, such as how much torque does the motor generate, how is it powered, what is its maximal speed, does the motor rotate only one way, and what are the consequences for rotational direction changes for bacterial swimming? One of the participant's videos is then analyzed by the faculty—first by converting the image time series of rotation to angle versus time traces via tracking tip of the cell furthest from the anchor point, then by computing a fast Fourier transform to obtain speed versus time traces. During this portion of the activity, some participants offer new and interesting alternatives for data analysis (some drawing on what they have learned in other laboratory sessions).



### 3.5. Modeling and Analysis

The interplay of modeling, theory, and experiment is key to modern research, which is particularly true for tabletop science because of the need to quickly adapt experiments to the discoveries being made. Yesterday's supercomputers are now readily available in pocket-sized devices so even low-budget research programs can produce high-quality modeling results. Virtual experiments can be run in idealized worlds, where every detail is controlled or measured. Such computational experiments enable rapid testing of simple ideas or complicated theories and can provide strong predictions for the real world. All computations and theories must bend to the reality of experiment and the interplay of modeling, theory, and experiment is stressed throughout the Hands-On Schools.

The Schools' modeling modules have three primary learning goals: (*a*) learn basic programming in a modern, fourth-generation computer language; (*b*) experience the power of computational experimentation by creating a general-purpose molecular dynamics (MD) simulation and modifying it to answer a participant-designed question; and (*c*) use modeling software for experimentation and analysis. Schools have featured a variety of modules with diverse topics; modeling themes have included dynamical systems, data encryption and information security, computational fluid dynamics, turbulence, biological systems, neural networks, analysis of differential equations, weather prediction, forecasting, chaos, disease modeling, and Kalman filtering.

The Schools' modules emphasize the importance of starting with a clear, well-defined question. For example, "Do foams behave like sticky spheres?" or "How do physical barriers affect disease spread?" We use classic methods such as MD simulations, partial and ordinary differential equation solvers, and finite-element solvers to attack these problems. The key tool is a computer with a fourth-generation programming language such as MATLAB, Python, Julia, Scilab, or Octave. MATLAB has been used most frequently because of its large user base, state-of-the-art just-in-time compiling with speeds similar to standard compiled languages like C++, built-in analysis and publishing tools, integrated work environment enabling a rapid cycle workflow, ease of learning, integration of parallel and GPU (graphics processing unit) computing, and rapid prototyping capabilities. While MATLAB is not free, the expense ($500 in 2022 for a perpetual license, comparable to computer hardware costs) is justifiable even for low-cost science; moreover, MATLAB allows participants' limited time at the Hands-On Schools to be better focused on science. We also discuss free alternatives to MATLAB (e.g., Jupyter notebooks with Python or Julia) with the participants.

**3.5.1. Activity: programming tutorial.** Participants have varying levels of computational skill; thus, the Schools' modeling curriculum begins with an introduction to programming module. After a 15-minute walk-through on how to start and set up the MATLAB integrated development environment, participants follow a self-guided tutorial. The tutorial assumes no prior programming knowledge and is broken up into sections so that more experienced programmers can easily skip ahead. School faculty circulate among the participants to field questions and give hints. After 1–1.5 hours, several programming projects are introduced; for example, a common project is to analyze a short video of a swinging double pendulum from an experiment performed by participants in a past Hands-On School (see **Supplemental Appendix** for details). The pendulum project complements work in typical tabletop experiments by teaching the participants how to load images, extract pixel and time information, and analyze the data. Participants propose different ideas for identifying and tracking the pendulum's motion; the proposals are collectively shared and consolidated, leading to solutions for working trackers.

Supplemental Material >

**3.5.2. Activity: molecular dynamics simulator.** The Schools feature a module based on discrete-element simulation, which is one of the most important tools in computational modeling. It is very general and allows participants to model everything from atoms to polymers, cells, birds, cars, and galaxies, and as described by Doyama (1999), it was among the earliest uses of modern digital computers including the MANIAC (Mathematical Analyzer Numerical Integrator and Automatic Computer Model I) (Metropolis et al. 1953) and the UNIVAC (Universal Automatic Computer) at CalTech (Alder & Wainwright 1957). In this activity, the participants learn the basics of trajectory-based MD and write their own simulator in order to teach participants how trajectories are calculated from positions, velocities, and forces. At the end of this 1- to 2-hour process, each participant has a working 2D simulation of $N$ linearly elastic disks in a rectangular container. For the remaining 1–2 hours, the participants formulate a question they would like to explore and then they modify their code to answer their question. **Figure 5** shows examples of simulations to answer the following four questions: (**Figure 5*a***) Does the shape of the container affect the packing density of spheres settling under gravity in 3D? (**Figure 5*b***) How do polymer rings pack? (**Figure 5*c***) What is the size of a long polymer as a function of temperature? (**Figure 5*d***) How does movement affect disease transmission?

**3.5.3. Activity: modeling applications.** The Schools also feature modules with topics and questions preselected by School faculty, primarily using prewritten computational tools to explore timely topics. In one module, "Modeling Dynamical Systems," participants learn about model

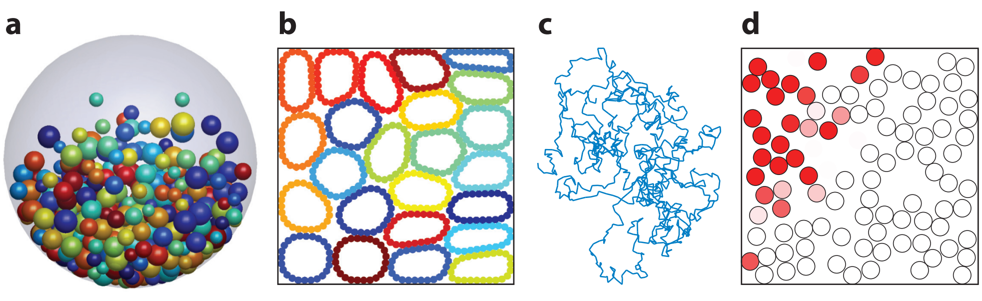


**Figure 5**

Molecular dynamics (MD) simulations developed by participants during various Hands-On Schools. (*a*) 3D model of spheres settling in a spherical container. (*b*) Compressing 2D loop polymers (closed chains). (*c*) Long 3D chains evolving in an MD simulation under NVT conditions (conservation of the amount of substance $N$, volume $V$, and temperature $T$). (*d*) Standardized infection ratio disease model with random contact spread. Color indicates contagion strength from an initial infection in the upper-left corner.

development, analysis, and interpretation of computational results using a variety of mathematical models. This module focuses on models using ordinary differential equations, and participants gain practice using MATLAB's differential equation solvers. Participants choose among several example problems, including dynamics and bifurcation diagrams for low-dimensional chaotic models, spatiotemporal chaos and predictability in a simplified weather model, and modeling the human immune system. In another module, "Mathematical Modeling of Biological Systems," participants apply physics principles and quantitative methods to model biological genetic control networks using three techniques. (*a*) Participants simulate the network behavior of Boolean dynamics models to study the dynamics of the systems such as attractors, trajectory, and stability; (*b*) simulate the network behavior using ordinary differential equations and exploring the phase space description of the dynamic systems, limit cycles, Hopf bifurcations, and saddle-node bifurcations, as well as how the biological systems use these properties to construct a stable control network; and (*c*) model the network using reverse engineering methods to find a network that can robustly perform a given biological function and be combined with logical deduction to understand how to place functional constraints on a network topology.

## 4. PROFESSIONAL DEVELOPMENT

A successful scientific career has important dimensions beyond excellence in conducting research. The Hands-On School provides several activities to strengthen skills in selected critical areas. A major component of the Schools' development program concerns scientific communication (Section 4.1). Other professional development sessions cover topics on teaching and learning methodologies, grant writing, and scientific ethics (Sections 4.2–4.4). More details on these topics can be found in the **Supplemental Appendix**.

Supplemental Material >

### 4.1. Scientific Communication

Effective communication of research is of central importance in the professional life of every scientist. However, mentorship of early-career scientists on the best practices in scientific communication is highly idiosyncratic, dependent on the widely varying communication predilections of research advisors. Further, communication skills are rarely taught in conferences and workshops. In contrast, the Hands-On Schools have six interactive afternoon sessions on oral and written communications. The participants are required to create a research poster for the School and to give a 2-minute oral snapshot (with at most two slides) based on their poster. Participants meet in small groups to improve their poster and their snapshot talk. The oral presentations and posters are evaluated by a faculty panel and by participants, and prizes are awarded for the best presentations and posters at the conclusion of the School. Another guided interactive session is focused on writing journal articles.

**4.1.1. Oral and poster communication.** A peer-driven approach in small groups provides constructive critiques of each participant's poster and presentation. Feedback focuses first on the draft poster submitted by each participant prior to the start of the School. The poster is displayed and collectively examined in silence in a group typically consisting of six participants and two faculty members. The session facilitator then selects someone other than the author to describe both what they understood and what was unclear after viewing the poster. Other participants are then invited to give their perspectives. A lively interchange between the poster author and their peers typically ensues, with the author receiving valuable suggestions for improvement.

For example, most posters contain too much detail and jargon. Increasing the font size of poster elements (e.g., the abstract, table, figure captions, labels) improves the readability of many posters. Reorganizing the poster layout in a logical fashion (e.g., column format, proceeding from top to bottom, left to right with numbered sections) helps readers follow the presentation. Judicious use of color helps readers glean the big picture from each poster. A summary of these and other suggested principles of effective posters is given by Block (1996), a copy of which is provided to each participant in the School.

After feedback, participants prepare revised posters that are printed for their formal presentations to the whole Hands-On School. A similar method is used to improve each participant's 2-minute oral presentation.

**4.1.2. Written communications.** In another small interactive session, participants receive training on how to write a journal article that will be understood and cited by other researchers.

***4.1.2.1. Choosing a title.*** Each participant is asked to write a title for a journal article on his or her research, keeping in mind that scientific articles are most often found in online searches using keywords. Participants are instructed to (*a*) make a list of words describing their research and use those words in generating possible titles, preferably with 10 words at most; (*b*) use words that will be broadly understood and attract interest; and (*c*) avoid jargon, clever double meanings, and imprecise words such as *new*, *novel*, *study of*, *investigation of*, *high-resolution*, *powerful*, or *efficient*. Each participant then presents his or her proposed titles to the group, and others comment on them and propose alternatives.

***4.1.2.2. Abstract.*** Participants receive suggestions about writing their abstract: (*a*) What have you done? (*b*) How did you do it? (*c*) What did you find that is new? (*d*) Why is it interesting? (*e*) What are the ramifications? The importance of succinctness and avoiding jargon is emphasized. The goal is to develop an abstract that will lead researchers who discover the paper to download and read it, rather than to move on to the next one in their literature search.

***4.1.2.3. Organization.*** Participants are asked to list the order in which they read sections of a research paper, which typically has these sections: introduction, background, methods, results, discussion, conclusions, and references. Discussions with participants reveal that almost no one reads straight through from the introduction to the conclusions. Many readers go first to the introduction and then skip to the figures, the results, or the conclusions. If there are unfamiliar terms in a figure caption or in the results section, readers often become frustrated and skip to the next paper in their literature search. Thus, each section of a paper should be as self-contained as possible.

***4.1.2.4. Figures.*** Many participants say that they turn to the figures after reading a paper's abstract. This emphasis on figures is not unreasonable because evolution has prepared us to interpret images much more quickly than text. Our ancestors learned to interpret images hundreds of millennia ago, while only a few generations ago the global literacy rate was still less than 10%. Hands-On School participants are encouraged to make each figure and its caption tell a self-contained story. The caption should begin with a short phrase or sentence stating the point illustrated by the figure and follow with the details. A recommended resource on preparing figures is *The Visual Display of Quantitative Information* (Tufte 2001), which emphasizes that one should maximize the ratio of ink representing data to the ink used for everything else, including axes, labels, arrows, and figure legends. Scientific writers should consider putting graphs with details on instrumentation and methods into a supplemental materials section.

***4.1.2.5. Methods.*** The training stresses that a methods section should provide all the information needed for readers to be able to replicate the results. Omission of essential information is unscientific and an indication of sloppy work with no lasting value. Give the range and units for each parameter. Researchers should state the initial conditions and boundary conditions in numerical simulations and describe how convergence was tested as a function of spatial and temporal mesh size. A theoretical paper should describe the assumptions, approximations, and normalizations.

***4.1.2.6. Results.*** The results section should describe succinctly what has been found. The order of the presentation should be logical rather than the order in which the results were obtained. All variables should be defined. Many curves on a graph or many panels in a figure can be overwhelming for a reader—only what is essential to convey the story should be included.

***4.1.2.7. References.*** The Hands-On training also stresses that proper and complete referencing of papers relevant to a writer's work is essential. Deliberate omission of a pertinent author or a particular paper is unethical and unacceptable, and inadvertent omission is a sign of sloppy science. Researchers should search for articles related to one's interests using online search engines such as scholar.google.com, webofscience.com, jstor.org, and arXiv.org.

***4.1.2.8. Revising.*** The most important advice on writing is to revise, revise, revise! Participants are encouraged to ask colleagues to critique their manuscripts, as well as to offer to read and comment on their colleagues' draft manuscripts. Colleagues who are not familiar with the subject are often able to discover unintelligible statements and other weaknesses.

## 4.2. Teaching and Learning

Most Hands-On School participants want academic careers in which they will be educators. In recent years, the Schools have taught research-based educational best practices, adapted for resource-constrained settings. Tutorials on both active learning methodologies and computational thinking are offered.

The active-learning technique of peer instruction (Mazur 1997) is introduced in a lecture setting with questions posed to participants, who step through the process in the role of students. First, participants reflect on the posed question and commit to an individual answer. Next, they discuss their thinking and answers with their peers. Lastly, they commit to a final individual answer. Management of the peer instruction process from the instructor's perspective is also discussed. Real-time student feedback is collected using effective low-tech methods—lettered flash cards instead of expensive clicker-based hardware. In some Schools, a follow-up tutorial session gives participants opportunities to practice the role of classroom instructor. Some Schools also offer a tutorial on the active learning technique of interactive lecture demonstrations (Sokoloff & Thornton 1997).

Many Schools also feature a tutorial on methods to foster computational thinking in undergraduate science and engineering students. Participants are introduced to VPython, which provides an intuitive programming environment for students that have little or no programming experience.

## 4.3. Grant Writing

In most Schools, an hour is devoted to grant writing, where about half the time is devoted to providing information, and the other half involves the discussion of issues and experience around writing projects and obtaining funding in LMICs. The faculty make an effort to provide up-to-date information on funding schemes and sources that would interest early-career researchers in LMICs, such as various ICTP programs. We also provide guidelines and links to other resources on how to write a compelling grant applications; this reinforces some of the communication skills and development concepts introduced in the first week.

### 4.4. On Being a Scientist: Ethics

Science depends very strongly on trust and a broad acceptance and sharing of ethical standards. In most Schools we hold an hour of debate about ethics. The material presented is typically a minimal list, mostly to define the scope of what is meant by "ethics" in our work. Almost all ethical dilemmas involve trade-offs; although in some cases there is an obvious, absolute right thing to do, in others one has to identify an in-between solution that might depend on personal environment and conditions. Topics that generate good discussions include (*a*) the fact that funding often comes with conditions and ties or might be on topics (e.g., weapons systems) that some will object to; (*b*) that rules and regulations sometimes seem to prevent speedy progress in science; (*c*) that the peer review of papers and grants depends strongly on the integrity of the individuals involved; (*d*) tensions and potential conflicts can arise between team members or in the dynamics with more senior faculty; and (*e*) examples of actual instances of malpractice and and ways of addressing them. The most engaging parts of these discussions concern specific difficult scenarios. The training often uses the publication *On Being a Scientist: A Guide to Responsible Conduct in Research* (Comm. Sci. Eng. Public Policy 2009).

## 5. OUTCOMES

Hands-On School participants have indicated the impacts of the School on their development by responding to an End-of-School Survey, as well as by contributing written reflections describing how School experiences influenced their career trajectories. A brief summary is given below; survey results and written reflections can be found in the **Supplemental Appendix**.

Supplemental Material >

### 5.1. End-of-School Survey

On the final day of the two-week program, participants respond to an anonymous, multipart End-of-School Survey: Part 1 probes participant views on the goals of the School, part 2 collects participant opinions on specific activities of the School, and part 3 asks for written comments about the School. The survey was administered at six distinct Schools beginning in 2014. The response rate has been uniformly high, averaging 86%. An overview of each survey part follows.

**5.1.1. Survey of Hands-On School goals.** An overwhelming number of participants indicated that the School was successful in meeting two goals that are in tension: (*a*) providing broad exposure to complex systems in a range of settings and (*b*) providing in-depth experiences in a few activities. Broad exposure was rated as personally important to 97% of participants; 98% of participants found that the School was helpful in meeting that goal. Similarly, in-depth experiences were rated as personally important to 94% of participants; 91% of participants felt that the School was helpful in meeting that goal.

Learning specific experimental skills was rated highly by 91% of participants; 92% of participants stated that the School was helpful in meeting that goal. 92% of participants rated learning simulation and computational modeling techniques as important; 86% of participants stated that the School was helpful in meeting that goal. Additionally, 94% of participants rated the development of career skills (e.g., scientific communication) as important; 91% of participants stated that the School was helpful in meeting that goal. 96% of participants also valued getting to know other scientists; 95% of participants said that the School was helpful in meeting that goal.

**5.1.2. Survey of specific School activities.** From among the laboratory, modeling, and simulation sessions, as well as the talks and professional development sessions offered at the School, participants were asked to select activities that they found particularly enjoyable or useful. Typically, in a given School, participants' expressed preferences were distributed broadly across most activities; moreover, since the content of most activities changed from year to year, no clear trends were discernible. However, professional development activities around scientific communication, which were repeated from year to year, stood out as exceptional and were identified as enjoyable or useful by an average of 66% of participants.

**5.1.3. Participant survey comments.** In the immediate aftermath of the School, most comments by the participants were strongly positive. Here are some examples: "I liked the fact that they combined theory with simple experimentation to make understanding of physics concepts easy." "I have gained confidence watching and learning from Hands-On sessions and have determined to improvise experiments that I have only been planning but not been able to do for a few years now." "All the talks were great and a few of them have made a permanent mark in my mind. I learned a great deal by interaction with the scientists." "[I received] very good advice during poster and snapshot and abstract [sessions]. These will help me my whole life."

Participants also offered feedback on ways to improve the School. For example, several participants in the first few Schools indicated that back-to-back scheduling of activities inhibited interactions; scheduling in subsequent Schools was adjusted to allow for more unstructured time to facilitate spontaneous interactions among participants and between School faculty and participants.

## 5.2. Testimonials

Several School participants have reported that their experiences in the School significantly influenced their careers long after the end of the program. While in many respects, the School's impacts were unique to the participants' own circumstances, some common themes emerge.

Several participants indicated that the School changed how they worked at their home institutions. In some cases the School altered how they thought about and carried out scientific research: "The HOS allowed me to learn how to practice good science with little means. Coming from Cameroon, it is usually very hard to get your research financed. After I graduated . . . my research teams . . . started finding a way to produce good research . . . and developed our own experimental devices" (C.V.N. Abbe, personal communication). Regarding MD simulations, 3D printing, and Arduino usage, one participant wrote that these techniques learned at the School "were implemented in my new lab starting from zero after the school, and now we are able to automate our experimental systems and acquire data in real time . . . This has been a low cost major improvement for my lab focused on the study of fluid dynamics and granular materials" (F.P. Vázquez, personal communication). After the School, another participant reported seeing "a shop with colorful rubber bands and I got the idea of image assemblies of rubber bands [as] a very simple model of the entangled structure of polymer rings" (L. Gómez, personal communication). For one participant, the School "dramatically changed my career . . . I got to know about . . . new research in the areas of soft matter and active matter physics . . . I got research ideas . . . on microfluidic devices and granular materials . . . [and] have published many articles in these research [areas]" (R. Chaud, personal communication). Another participant reported that the School "taught me how to model natural phenomena mathematically and changed my life" (A. Elshayeb, personal communication). Participants also reported how lessons learned from the Schools were passed on to others at their home institutions: "When I returned to Cuba, I took . . . the knowledge I got and transferred it to my students. I organized a few exams for undergraduate students in this format of [brief oral communications] and the feedback was very good. I used the molecular dynamics simulations . . . as the core content to teach an introductory course of programming to physics students" (G.V. Lopez, personal communication). "I teach [techniques from the School] to our undergraduate students in Physics Lab every year" (F.P. Vázquez, personal communication).

The School caused some participants to rethink the trajectory of their careers: "I participated [in the School] when I was still a PhD student . . . I am [now] the Dean of the Graduate School at [the University of The Phillipines Los Baños] . . . [The School] contributed to this, especially in breaking barriers" (J. Rabajante, personal communication). Another participant wrote that at the time of the School, "I was working as a lecturer . . . Currently, I am serving as associate professor and chair of the Department of Natural Sciences at the Begum Nusrat Bhutto Women University [Pakistan]" (R. Chaud, personal communication). Another participant reported (C.V.N. Abbe, personal communication), "The [School] helped me [with] science communication skills, since [then], I have organized more than 20 seminars where I applied the techniques learned from the [School]." In other cases, the School inspired exploring scientific careers abroad: "In the school, I learned how to communicate science better, and how to interact with other people of different nationalities and backgrounds. . . the School definitely reinforced my interest to do a career in research. . . fast-forward to 6 years later, I finished my Ph.D. . . . at the Swiss Federal Institute of Technology" (A. Tarun, personal communication). "[The School] was definitely a significant catalyst that propelled my academic career . . . [and] opened me to numerous practical sessions and lectures . . . I was able to thereafter apply for a Fulbright scholarship in Trinidad and Tobago [which enabled pursuit of] a PhD in Atmospheric Sciences [at] the University of Missouri" (S. Balkissoon, personal communication). "The feedback [from the School] has helped my research to go in the right direction . . . Two years after the Hands-On School, I managed to secure a scholarship from the Italian Ministry of Foreign Affairs and International Cooperation (MAECI) . . . I am really excited to see where this journey will take me next" (G. Andadari, personal communication).

Some participants reported that the network of scientific relationships established at the School was particularly impactful: "Meeting participants from different countries having the same passion for science and performing experiments and activities was very great and inspiring" (O. Hamdy, personal communication). "I had the opportunity to spend time and discuss some topics related to my Ph.D. with people from different countries. Therefore, this school was fruitful and allowed me to create a good scientific network" (N. Roas, personal communication). "In the School, I learned . . . how to interact with other people of different nationalities and backgrounds" (A. Tarun, personal communication). In some cases, participants continued to interact and to establish collaborations long after the end of the program: "I keep in touch with many of the friends I made those days!" (G.V. Lopez, personal communication). "I found wonderful friends from all around the world during the [School], and we still follow closely our scientific careers and share some of our publications" (F.P. Vázquez, personal communication). One participant established a collaboration with a School faculty member and performed experiments with them that resulted in a publication in *PNAS* (Gómez et al. 2020).

## 6. OUTLOOK

The two types of venues where the Hands-On Schools have been offered have distinct advantages. The Schools have been presented either as a recurring program housed at the ICTP main campus or as a traveling program hosted for a single time at an institution that is geographically close to most participants' home institutions. Hosting Schools at a centralized location like the ICTP main campus offers the significant advantages of a dedicated infrastructure (housing and lab space) and experienced administrative support for international faculty and participants; it also makes global diversity in the participants possible. There are substantially increased costs associated with reproducing similar infrastructure and support at Schools that travel: Although support from institutions hosting the School helps to offset those costs to a degree, the cohort tends to be more regional. However, regional Schools offer opportunities to demonstrate tabletop experimental science in an environment that is more authentic, that is, more similar in resource access to that in the participants' home institutions than that in the facilities embedded in a developed country like Italy, where ICTP is located. Future Schools will explore alternatives that provide the best of both kinds of venues; for example, future Schools could be held at the ICTP institutes in Mexico, Brazil, Rwanda, and China.

A particular challenge of the Hands-On School program is finding new ways to support participants after their return to their home institutions. In some cases, participants continue collaborations that nucleated at the School. A few such collaborations of School classmates are continuing, but to date such examples have been episodic. Additionally, efforts of School faculty to foster post-School research collaborations with participants have not been successful. A key difficulty is that, upon return to their home institutions, participants often encounter barriers in applying lessons learned from the School in a sustainable way. One possible solution to this difficulty is to alter the recruitment strategy by inviting larger numbers of participants from some institutions to apply. Having a group of participants from the same institution (including an institute leader with access to local resources) experience the School together may provide the critical mass necessary for sustaining School practices upon return after the School.

In 2020, the onset of the COVID-19 pandemic led to the suspension of the Hands-On Schools program. Resumption of in-person activities that are essential to the School's operation has been hampered by global disparities in efforts to achieve disease immunity, coupled with repeated waves of increased infection fueled by mutations of SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2). As COVID-19 progresses from a pandemic to an endemic disease, the Hands-On Schools program is expected to resume.



## DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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Supplemental Material >

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## Errata

An online log of corrections to *Annual Review of Fluid Mechanics* articles may be found at http://www.annualreviews.org/errata/fluid