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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-to-middle income countries (LMICs).

Contents

1. INTRODUCTION

Tabletop experiments have a long and storied history in fluid dynamics: Henri B´enard's elegant observations of convection cells in a thin fluid layer heated from below (B´enard (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 are 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 environment.

Beginning in 2008, a series of Hands-On Research in Complex Systems Schools was created to provide a mechanism to help unlock the potential for widespread top-notch tabletop science. A listing 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-to-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

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

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

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 goal is to empower scientists all over the 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 also believe locally-driven science can create solutions and technological development in unique ways. For example, fostering investments in local ownership of research questions is likely to deliver substantial impacts and technological fallout with societal benefits that differ significantly from investments of 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 impacts of the Hands-On Schools, and Section 6 discusses the outlook and lessons learned for future Schools.

2. STRUCTURE OF HANDS-ON SCHOOLS

Most participants in the Hands-On Schools come from low and middle income countries (LMICs). For the Schools based at the International Center for Theoretical Physics (ICTP) in Trieste, there were typically 50-75 participants per summer, and each summer's School typically had 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 School participants coming from LMICs in South Asia, Latin America, Sub-Saharan Africa, and East Asia, respectively. In all Schools, most selected participants are early-career (graduate students, postdoctoral scholars and early-career faculty) in engineering, mathematics, and the physical, chemical and biological sciences. On average, approximately one-third of the participants are women.

Over the years, the School's format has been optimized. Recent programs operate for ten working days with about ten 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 Schools. During each morning, participants rotate into one of 10-12 half-day lab sessions featuring either intensive experimental or computational modeling activities. During 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 learning goals for the School's Hands-On 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 mechanics (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 Materials give additional information on these experiments and describe additional tabletop experiments and techniques from other disciplines.

3.2. Fluid Dynamics

Tabletop studies of fluid flows play a key role in advancing understanding of and developing solutions to numerous problems encountered by people 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) introduces Hands-On 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 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 2-dimensional turbulence, microfluidics, surface-tension-dominated flows) as well as tutorials on fluid dynamics modeling can be found in the Supplemental Materials.

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. (See Borrero-Echeverry (2018) for detailed plans.) The inner cylinder is driven with an inexpensive NEMA23 stepper motor, although any DC motor with precision control, such as a servo-motor, would also be appropriate. The inner cylinder rotation frequency, which is proportional to the flow's control parameter (the Reynolds number R), is precisely controlled using an inexpensive microcontroller programmed with open-source PYTHON software . 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 in Borrero-Echeverry et al. (2018). The visualized flow is illuminated using inexpensive LED 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-Couette 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_{cyl}, the rotation frequency of the inner cylinder, in a systematic fashion, while the outer cylinder is held at rest. For small f_{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, $v_\theta(r_i) = 2\pi r_i f_{cyl}$ and $v_\theta(r_o) = 0$, which yields $A = -2\pi f_{cyl} r_i^2/(r_o^2 - r_i^2)$ and $B = -Ar_o^2$ (Taylor (1923)). An analysis and experiment by Taylor (1923) showed that when f_{cyl} is increased, a critical rotation frequency f_c (corresponding to Reynolds number $R_c = 2\pi f_c r_i(r_o - r_i)$) 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_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 to determine the threshold of instability in *any* type of system 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_{cyl} takes an unnecessarily long time to find the onset of instability at $f_{cyl} = f_c$, 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 (non-hysteretic) 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_c with an uncertainty less than one percent in only a half-hour using a binary search. They then compare the 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

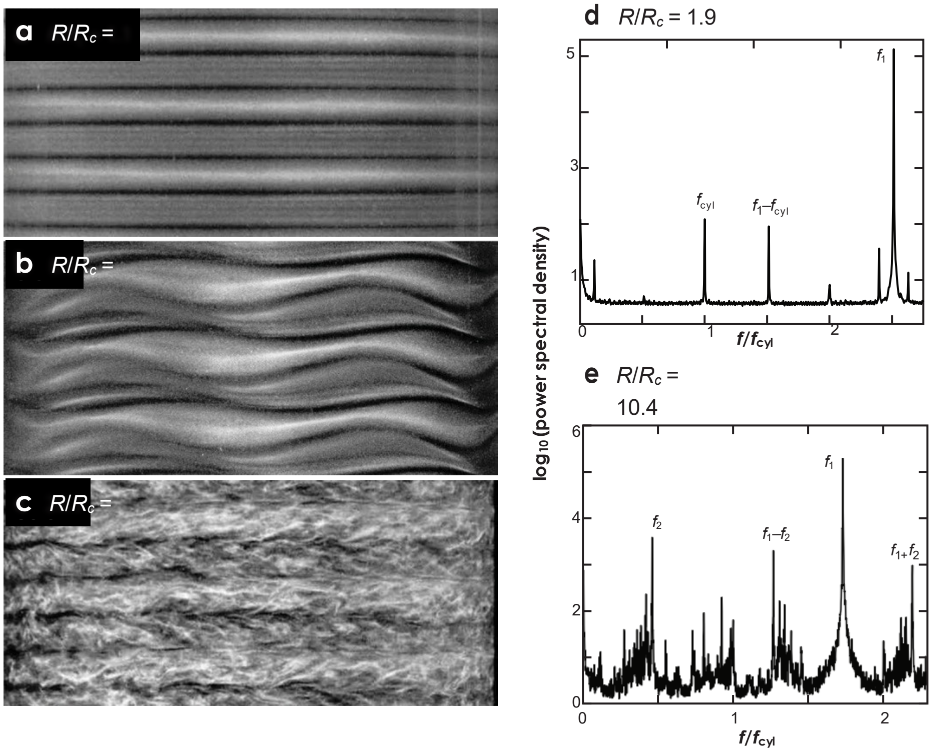

Figure 1: (a) The time-independent pattern of vortices that form at the first instability of fluid flow between concentric cylinders with the inner cylinder rotating and the outer cylinder at rest. The horizontal lines are boundaries between adjacent toroidal vortices that encircle the inner cylinder and are stacked along the cylinder axis. The Reynolds number R (proportional to the cylinder frequency f_{cyl}) is a measure of the system's distance from thermodynamic equilibrium. The critical Reynolds number R_c is the value of R at which the vortices emerge. (b) When R is increased sufficiently far above R_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 (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_{cyl}, which appears because the cylinder is not perfectly circular. (e) With increasing R, another instability occurs, as shown in (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_{cyl}.

a time-periodic state (a Hopf bifurcation) occurs in many systems at a precise value of the control parameter characterizing the system's distance away from equilibrium. Participants analyze the dynamics of the flow by recording videos at different cylinder rotation rates and determining the temporal frequencies in the flow pattern from video images using a MATLAB spectral analysis program.

Spectral analysis is an important and common tool in science, but it is new to many

Hands-On participants. Figure 1 shows the types of flow states analyzed by Hands-On participants. The power spectral density, computed from the time-varying intensity of a small region in the video image of the flow pattern in Figure 1(b), contains 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 a video, how to distinguish harmonics from additional fundamental frequencies, and how averaging over thousands of pixels reduces noise in the data and reveals sharp spectral peaks even though an analysis of data from a single pixel in the video might be too noisy to 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 and 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 participants. Multi-dimensional 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, $I(t_j)$, where $t_j = j\Delta t$, and $j = 1, \ldots, N$ with N large, e.g., 2^{12}. The time interval Δt 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 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 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 in (Roux et al. (1983)), and for analyzing chaotic (strange) attractors in (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, as the materials of life) 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 and time scales) enables 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 School's hands-on laboratories: granular matter and colloids composed of Brownian or active (self-propelled) particles. Granular matter experiences prepare participants to engage in scientific advances necessary to address relevant societal applications involving highly dissipative matter, including soil remediation, mining and resource extraction, erosion, and water purification (Nagel (2017)). Development of expertise in colloidal experimental methods opens up opportunities for participants to explore the basic science behind a variety of consumer products, and 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 Materials.

The hands-on 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 were 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 progression of low-cost microscopes were built for the colloidal experiments: initially microscopes were built using lenses and metal clamps, in later Schools open hardware projects were featured (e.g., 3D printing of microscope stages, encouraging use of the 100 USD OpenFlexure Microscope (OpenFlexure.org (2022))). Light emitting diodes (LEDs) provided 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 provided vibration combined with field programmable gate arrays (FPGA) and Arduino-like micro-controllers to create synchronized stroboscopic LED illumination. Custom software codes were written in both PYTHON and MATLAB for image acquisition and analysis as well as experimental control.

3.3.1. Activity: Dynamic Differential Microscopy (DDM) 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 $D = k_B T/(6\pi\eta r)$ linking the diffusion coefficient D to the Boltzmann constant k_B, the temperature T, the viscosity η 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 super-diffusive if there is active propulsion or if the particles are being advected by fluid flows. Measurements of such motions are critical to elucidate 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 τ are subtracted and the corresponding 2D spatial Fourier transform is computed. By repeating this process for subtracted images for a range of different τ, an intermediate scattering function can be determined (Giavazzi et al. (2008)), which robustly characterizes particle motion (Figure 2).

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

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 seconds in length. Prewritten, commented MATLAB scripts for DDM analysis are provided and discussed in a step-by-step manner. (The MATLAB script can be readily ported to open-source codes like PYTHON.) An experimental run (from image acquisition to DDM analysis) takes a manner of 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

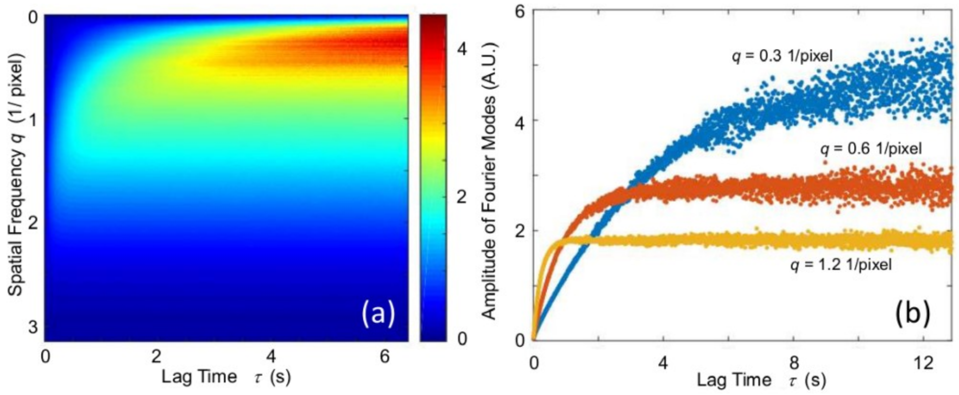

Figure 2: DDM analysis of images from videomicroscopy enables classification of motion and identification of dynamical parameters, even when very basic optics and mechanics are used. From FFT of image-differences, averaged for equal lag times and azimuth, a sample of colloidal particles will display a signal that grows with lag time, to some saturation value, and peaks at some finite spatial frequency which depends on the optics (a). These data are typically investigated as a function of lag time, (b), for some values of spatial frequency. The data can be fitted to extract a timescale τ_q, where the q-dependence describes the type of motion (e.g. sub-diffusive, diffusive, ballistic); moreover, in the cases of diffusive and ballistic motion, the prefactor quantifies precisely the diffusion coefficient or the velocity, respectively.

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 this 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 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 a number of 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 20 D high and 17.5 D 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 particles to fluctuate when the particles are in motion. This granular system is "heated" by the sinusoidal motion of the

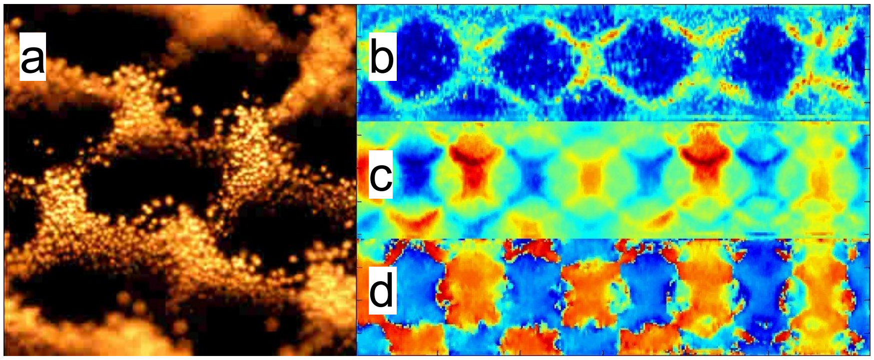

Figure 3: (a) Snapshot of vertically vibrated 165 μm bronze spheres showing one phase of a square pattern formed at low driving frequency. (b) Frame from participants' movie showing square patterns in cell with aspect ratio, length over width, $L/W = 4.5$. (c-d) Images of the time-independent amplitude (c) and phase (d) extracted from the movie in (b) by School participants.

container's bottom boundary mechanically connected to a loudspeaker driven by 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 $D/1000$) in every movie. From the particle track data, the participants extract time-dependent particle densities, velocities, granular temperatures, as well as, system-averaged container volume and particle kinetic energy. The participants observe a hysteretic phase transitions between crystalline and gaseous states as A is increased and decreased. From these observations, participants compute the gas compressibility $x(A, f)$ and note that x changes discontinuously as the system crystallizes. Additionally, participants find in the gaseous phase (at fixed f), x 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, $x(A, f)$ collapses when plotted as 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 this laboratory, participants ex- plore pattern formation in vertically vibrated thin granular layers; experimental study of these behaviors test continuum theories of granular flows. In a rectangular dish of size

101.6 mm by 25.4 mm, participants placed a 1-4 mm layer of 0.165 mm-diameter bronze spherical particles. The dish of particles is vertically vibrated by mechanical connection with a loudspeaker driven by participant-programmed sinusoidal waveforms with 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, a field programmable gate array (FPGA), configured as a phase-locked-loop, was 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 were 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 sub-harmonic, oscillating at a frequency of $f/2$, and that the type of pattern observed is determined by the non-dimensional 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 $A(,x)$ from movie snapshots of the form $M(,x,t) = \Re[A(x) \exp(2\pi i f_d t)]$ using demodulation at frequency f_d. By varying f_d, the full phase behavior of the pattern can be mapped out. For the range of Γ and f^* we studied, there is only one significant $A(,x)$ for $f_d = f/2$. The amplitude $|A(x)|$ and phase $\mathbf{Arg}(A(,x))$ 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, as well as to uncover new physical concepts.

Bacteria are studied in a number of hands-on laboratories. 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 School's physics of living systems laboratories are in the Supplemental Materials.

The hands-on laboratories familiarize participants with techniques and limitations of tabletop bacterial studies under resource-constrained environments. Data acquisition in the bacterial labs emphasize 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 non-pathogenic organisms (Biosafety Level 1 (BSL-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 who is observed to make mistakes in sterile techniques is required to re-do steps with 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 Materials for further details).

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

3.4.1. Activity: Antimicrobial efficacy and diffusion. Participants use disk diffusion assays (Hudzicki (2009)) to probe inhibition of bacterial growth by antimicrobal agents. Three antimicrobal candidates are tested: ethanol, hydrogen peroxide, and eucalyptus oil. These are cheap, readily available, and do not require refrigeration. Participants spread 5 droplets (from a pre-sterilized, disposible plastic dropper) of a suspension from overnight culture of bacterium *Escherichia coli* on sterile nutrient agar plates, place sterile paper disks on the inoculated plates, and place on each disk one drop of different candidate antimicrobial solution. Participants then set aside for incubation the plates they prepared (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 indicated locations where bacteria are killed or inhibited. The size of the cleared region will depend on properties of the specific candidate antimicrobial, including the amount applied, diffusion constant, and efficacy against the bacteria being tested (See top of Figure 4 and Bonev et al. (2008), Kaushik et al. (2015b), Edward (1970)). At the end of each session, participants inoculated liquid cultures to grow overnight and be used by the next day's class.

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 bioprospecting for antimicrobial materials and how it could be used to assess the efficacy of commercially-purchased products (Freire-Moran et al. (2011), Newman & Cragg (2020), Höjgård (2012)). Since most of the materials used in this experiment are pre-prepared by School faculty, participants are provided with videos showing preparation. The videos, along with a a fuller description of this laboratory are in (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), Ajaev & Davis (1998), Berry & Berg (1997), 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 non pathogenic *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 Materials for details). 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 (See Figure 4(e) and (f)). Participants view (after focusing the microscope) and record

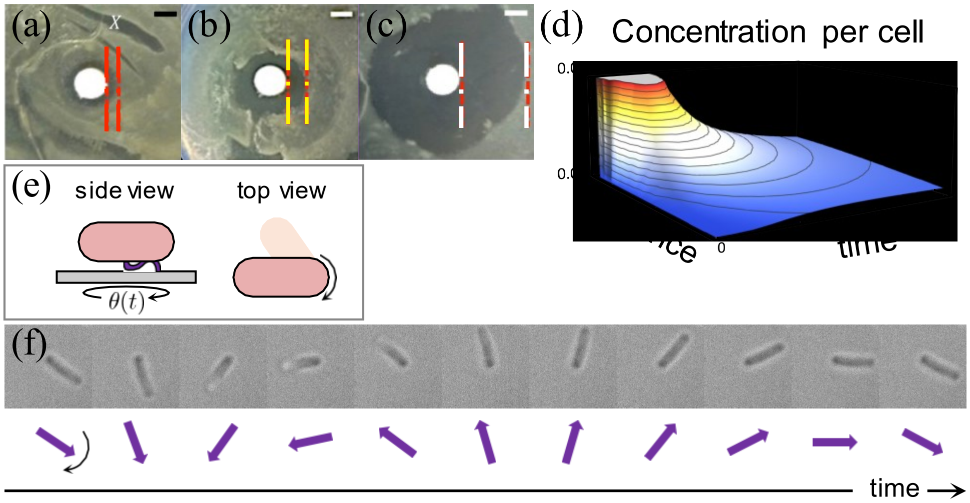

Figure 4: (a-c) After bacteria on the plate have been allowed to grow overnight, bacteria-free regions, called "zones of inhibition", are seen around filter disks. The size of the zones of inhibition is set by the distance from the filter paper disk that the antimicrobial factor reached when its per-cell concentration dropped to the growth-inhibiting threshold. Panels a, b and c show samples prepared by students at the School using eucalyptus oil, ethanol, and hydrogen peroxide, respectively; red dashed lines in these panels indicate the size of the zone of inhibition, which was published and here reproduced from Kaushik et al. (2015a), used under Creative Commons License. (d) When an antimicrobial solution is applied to a filter paper disk on an agar plate on which bacteria have been spread, 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 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) A cartoon of an *E. coli* bacterial cell tethered to the surface of a microscope cover slip (side and top view are shown). The bacterial flagellar motor (indicated by a small green rectangle, not to scale) is anchored to the cover slip surface by a bacterial flagellar filament, shown in purple. Rotation of the motor then rotates the entire cell body. A cartoon of an *E. coli* bacterial cell tethered to the surface of a microscope cover slip (side and top view are shown). Ordinarily, about half a 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 is shown, with purple arrows indicating the rotational direction of the cell body driven by the anchored bacterial flagellar motor.

the cell rotation; this is the most visually engaging part of the experiment, and generates excitement among the participants.

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, e.g. how much torque does the motor generate, how it is 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 an FFT 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 super-computers 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:(1) Learn basic programming in a modern, fourth generation computer language. (2) Experience the power of computational experimentation by creating a general purpose molecular dynamics simulation and modifying it to answer a participant-designed question. (3) 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 molecular dynamics, 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 like MATLAB, PYTHON, JULIA, SCILAB, OCTAVE, etc. MATLAB has been used most frequently because of the 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 allowing a rapid cycle workflow, ease of learning, integration of parallel and GPU computing, and rapid prototyping capabilities. While MATLAB is not free, the expense (USD 500 in 2022 for a perpetual license, comparable to computer hardware costs) is justifiable even for low-cost science; moreover, MATLAB enables the participants' limited time at the 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 setup the MATLAB integrated development environment, the participants follow a self-guided tutorial. The tutorial assumes no prior programming knowledge and is broken up into sections so that more ex-

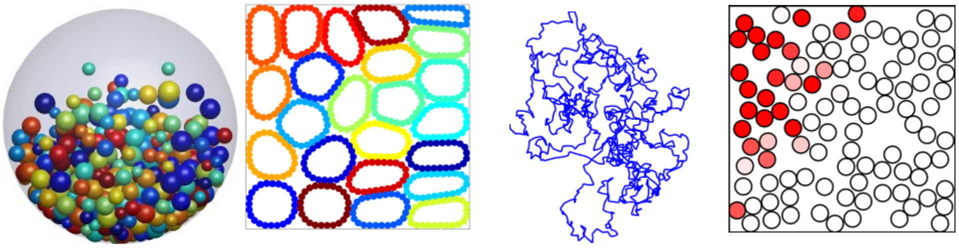

Figure 5: Examples of participant Molecular Dynamics simulations developed during various Hands-On Schools. Left-to-right: 1. 3D model of spheres settling in a spherical container. 2. Compressing 2D Loop ”polymers” (closed chains). 3. Long 3D chain evolving in a Molecular Dynamics simulation under NVT conditions (i.e. where the amount of substance (N), volume (V) and temperature (T) are conserved). 4. Standardized Infection Ratio (SIR) disease model with random contact spread. Color indicates contagion strength from initial infection in upper-left corner.

perienced programmers can easily skip ahead. School faculty circulate amongst the participants fielding questions and giving 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 Materials 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 then 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.

3.5.2. Activity: Molecular Dynamics (MD) simulator. The Schools feature a module based on discrete-element simulation, which is one of the most important tools in computational modelling. It is very general and allows participants to model everything from atoms to polymers to cells to birds to cars to galaxies and was one of the first computer programs ever written (Metropolis et al. (1953), Alder & Wainwright (1957), Doyama (1999)). In this activity, the participants learn the basics of trajectory-based MD and write their own simulator, which teaches participants how trajectories are calculated from positions, velocities, and forces. At the end of this 1-2 hour process each participant has a working 2D simulation of N linearly elastic disks in a rectangular container. For the remaining 1-2 hrs the participants form a question they would like to explore, and then they modify their code to answer their question. Fig. 5 shows examples of simulations to answer the following four questions: (1) Does the shape of the container affect the packing density of spheres settling under gravity in 3D? (2) How do polymer rings pack? (3) What is the size of a long polymer as a function of temperature? (4) How does movement affect disease transmission?

3.5.3. Activity: Modeling applications. The Schools also feature modules with topics and main questions pre-selected by School faculty primarily using pre-written computational tools to explore a timely topic. An example of these modules is (A): “Modeling Dynamical Systems”, where participants learned about model development, analysis, and interpreta- tion of computational results using a variety of mathematical models. This module focuses on models that are ordinary differential equations, and participants gained practice in using MATLAB's differential equation solvers. Participants choose among several example problems like dynamics and bifurcation diagrams for low-dimensional chaotic models, or spatio-temporal chaos and predictability in a simplified weather model, or modeling the human immune system. Another example is (B): "Mathematical Modeling of Biological Systems", where participants apply physics principles and quantitative methods to model biological genetic control network using three techniques: (1) Simulating the network behavior of Boolean dynamics models, and study of the dynamics properties of the systems such as attractors, trajectory, and stability. (2) Simulating 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. (3) Model the network using reverse engineering methods to find a network that can robustly perform a given a biological function and can be combined with the logic deduction method 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 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 including teaching and learning methodologies, grant writing, and ethics (Sections 4.2-4.4). More details on these topics, as well as on activities on specialized experimental techniques and extended explorations of topics introduced in the hands-on laboratory sessions can be found in the Supplemental Materials.

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 2 slides) based on the 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 and figure captions and labels, etc.) 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 can be found in 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.

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: (1) make a list of words describing their research and use those words in generating different possible titles, preferably with ten words at most, (2) use words that will be broadly understood and will attract interest, (3) avoid jargon, clever double meanings, and imprecise words such as "new, novel, study of, investigation of, high resolution, powerful, efficient." Each participant then presents his or her proposed titles to the group, and others comment on the different titles and propose alternatives.

Abstract. Participants receive suggestions about writing their abstract: (1) What have you done? (2) How did you do it? (3) What did you find that is new? (4) Why is it interesting? (5) 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 a paper to download and read that paper, rather than to move on to the next paper that appears in their literature search.

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 or to the Results or to the Conclusions. Readers often become frustrated if there are unfamiliar terms in a figure caption or in the Results section, and then they skip to the next paper that appeared in their literature search. Thus each section of a paper should be as self-contained as possible,

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 participants are encouraged to make each figure and its caption tell a self-contained story. Begin the caption 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. Consider putting graphs with details on instrumentation and methods into a Supplemental Materials section.

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. 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.

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. Define all variables. Many curves on a graph or many panels in a figure can be overwhelming for a reader – include only what is essential to convey the story.

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. Search for articles related to your interests by using online search engines such as *scholar.google.com*, *webofscience.com*, *jstor.org*, and *arXiv.org*.

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

4.2. Teaching and Learning

Most 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 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, reflecting on the posed question and committing to an individual answer, next discussing their thinking and answers with their peers, then committing 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 provides information, and the other half discusses issues and experience around writing projects and obtaining funding in LMIC. The faculty make an effort to provide up to date information on funding schemes and sources that would interest early career researchers in LMIC, for example, various ICTP programs. We also provide guidelines and links to other resources on how to write a compelling grant application; this reinforces some of the concepts of the communication-skills development introduced in the first week.

4.4. On Being a Scientist: Ethics

Science depends very strongly on trust and on 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 are tradeoffs of sorts; 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. The topics that generate good discussions include: (1) funding comes with conditions and ties, and might be on topics (e.g. weapons systems) that some will object to; (2) rules and regulations sometimes seem to prevent speedy progress in science; (3) the peer review of papers and grants depends strongly on the integrity of individuals involved; (4) the tensions and potential conflicts that can arise between team members, or in the dynamics with more senior faculty; (5) examples and ways of addressing actual instances of malpractice. The most engaging parts of these discussions are on specific "difficult" scenarios. The training often uses the publication "On Being a Scientist: A Guide to Responsible Conduct in Research" (Committee on Science, Engineering and Public Policy (2009)).

5. OUTCOMES

Participants have indicated the School's impacts on their development by responding to an End-of-School Survey and 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 Materials.

5.1. End-of-School Survey

On the final day of two-week program, participants respond to anonymous, multi-part 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 with HOS14. 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 indi- cated that the School was successful in meeting two goals that are in tension: (1) Providing broad exposure to complex systems in a range of settings, and (2) providing in-depth ex- periences in a few activities. Broad exposure was rated as personally important to 97%

of participants; 98 % of participants found the School was helpful in meeting that goal. Similarly, in-depth experiences was rated as personally important to 94 % of participants; 91 % of participants felt the School was helpful in meeting that goal.

Learning specific experimental skills was rated highly by 91 % of participants; 92 % of participants stated 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, and 95 % of participants said the School was helpful in meeting that goal.

5.1.2. Survey of Specific School Activities. From among the laboratory, modeling, and sim- ulation sessions, and 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 . . . "
- ".. 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, a number of 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

A number of participants report that 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 the School changed how they worked at their home institutions. In some cases the School altered how they 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 ...” (Abbe (2021)). “...[techniques from the School including molecular dynamics simulations, 3D printing and Arduino usage] were implemented in my new lab started 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.” (Vazquez (2021)). “...[After the School] I saw 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...” (G´omez (2021)). “[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]...” Chaud (2021). “[The School] taught me how to model natural phenomena mathematically and changed my life...” (Elshayeb (2021)). 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...” Lopez (2021)). “I teach [techniques from the School] to our undergraduate students in Physics Lab every year...” (V´azquez (2021)).

The School causes 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...” (Rabajante (2021)). “...[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]...” (Chaud (2021)). “... 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]...” (Abbe (2021)). 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 background... 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 ...” (Tarun (2021)). “...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 ...” (Balkissoon (2021)). “... 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...” (Andadari (2021)).

Some participants reported the network of scientific relationships established at the School were particularly impactful. “Meeting participants from different countries having the same passion for science and performing experiments and activities was very great and inspiring...” (Hamdy (2021)). “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..." (Roas (2021)). "In the School, I learned ... how to interact with other people of different nationalities and backgrounds..." (Tarun (2021)). 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!" (Lopez (2021)). "...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..." (Vazquez (2021)). ".[established a collaboration with a School faculty member and performed experiments together] ... we published ... work in PNAS..." (Gomez (2021), G´omez et al. (2020)).

6. OUTLOOK

The two distinct types of venues in which the Hands-On Schools have been offered have different advantages. The Schools have been presented either as a recurring program housed at the ICTP main campus, or as a traveling program hosted a single time at an institution that is geographically close to most participants' home institutions. Hosting Schools at centralized location like the ICTP main campus offers significant advantages in dedicated infrastructure (housing, 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, i.e., more similar in resource access in the participants' home institutions than the facilities embedded in a developed country like Italy, where ICTP is located. Future Schools will explore alternatives that provide the best of both 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 such examples have been, to date, episodic. Also, 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 the SARS-CoV-2 virus. As COVID-19 progresses from a pandemic to an endemic disease, the Hands-On Schools program is expected to resume.

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