Research Interests – Raymond E. Goldstein

I. Overview

When asked whether I am a theorist or an experimentalist, my reply is that I am a scientist. Our group seeks to understand fundamental principles that govern the behavior of nonequilibrium systems in physics and biology, using a combination of experiment and theory. This research is not easily described by a single, conventional academic label; rather, it involves the domains of condensed matter physics, physical chemistry, biological physics, fluid dynamics, applied mathematics, and geophysics. I subscribe to Poincaré's motivation: *The scientist does not study nature because it is useful; he studies it because he delights in it, and he delights in it because it is beautiful. If nature were not beautiful, it would not be worth knowing, and if nature were not worth knowing, life would not be worth living.*

Current research in my group falls into three broad categories: Biological Physics, Fluid Dynamics & Chemical Pattern Formation, and Mathematical Physics.

II. Biological Physics

Biological physics is the largest part of our research program. We are primarily concerned with fluid dynamics at the scale of individual cells, solute transport and collective behavior driven by self-propulsion, and, increasingly, the deep questions surrounding the physics of multicellularity. Experimental methods include microscopy, fluorescence, optical trapping, particle imaging velocimetry, and various biochemical interventions. Below I describe six projects of current interest, some quite far advanced, others under development.

The Chemotactic Boycott Effect: Aerobic bacteria often live in thin fluid layers near solid-air-water contact lines, where the biology of chemotaxis, metabolism, and cell-cell signaling is intimately connected to the physics of buoyancy, diffusion, and mixing. Using the geometry of a sessile drop have demonstrated in suspensions of *B. subtilis* the self-organized generation of a persistent hydrodynamic vortex which traps cells near the contact line. Arising from upward oxygentaxis and downward gravitational forcing, these dynamics are related to the Boycott effect in sedimentation, and are explained quantitatively by a mathematical model consisting of oxygen diffusion and consumption, chemotaxis, and viscous fluid dynamics. The vortex is shown to advectively enhance uptake of oxygen into the suspension and the wedge geometry leads to a singularity in the chemotactic dynamics near the contact line. The image shows (top) measured streamlines near the contact line, found using particle imaging velocimetry (PIV) with suspended fluorescent microspheres. The bottom image shows a finite-element calculation of the same.

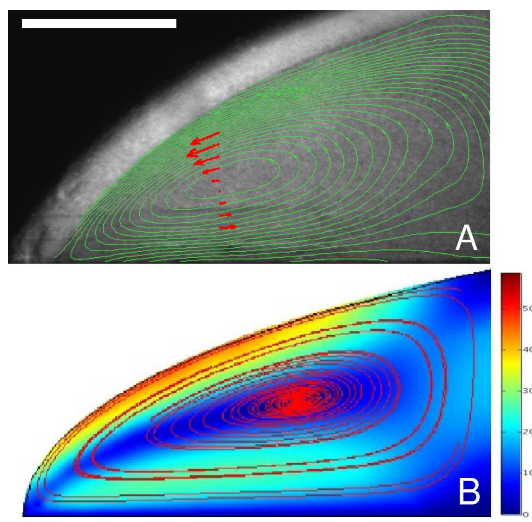

Figure 1: *Hydrodynamic vortex in a drop of bacterial suspension, and in a numerical computation. Scale bar is* 1 *mm.*

•"Bacterial Swimming and Oxygen Transport Near Contact Lines," I. Tuval, L. Cisneros, C. Dombrowski, C.W. Wolgemuth, J.O. Kessler, and R.E. Goldstein, *Proc. Natl. Acad. Sci. (USA)* **102**, 2277-2282 (2005).

Collective Dynamics in Bacterial Suspensions: The chemotactic Boycott effect described above leads to extremely high concentrations of bacteria near the contact line of sessile drops and at the bottom of pendant drops. On scales much larger than a cell, concentrated regions in both geometries exhibit transient, reconstituting, high-speed jets straddled by vortex streets. We have termed this the "zooming bio-nematic phase." The image shows a typical bacterial swimming velocity field obtained from PIV analysis. The autocorrelation function of the velocity obtained from a sequence of such vector fields shows order persisting for distances exceeding 100 microns, with a lifetime on the order of 2 seconds and velocities than can reach 100 microns/s. The Peclet number is thus considerably larger than unity. A mechanism for large-scale coherence is proposed based on hydrodynamic interactions between swimming cells. These results have implications for cell-cell signaling in dense suspensions and challenge theories of the ordering of self-propelled particles.

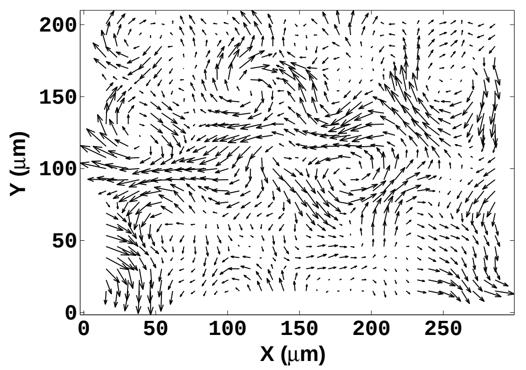

Figure 2: *Swimming velocity field in the zooming bio-nematic phase, showing jets and vortices.*

•"Self-Concentration and Dynamic Coherence in Bacterial Dynamics," C. Dombrowski, L. Cisneros, S. Chatkaew, R.E. Goldstein and J.O. Kessler, *Phys. Rev. Lett.* **93**, 098103 (2004).

Swimming, Stirring, and Scaling in the Volvocales: The exchange of metabolites by suspended microorganisms, signaling between them, and chemotactically oriented locomotion all depend on the dynamics of molecular transport. Near an organism, convention views transport as almost exclusively dominated by the diffusive spread of molecular solutes. Yet, the flagella that propel cells inevitably stir up the fluid through their high-speed rotation and bundling dynamics. For individual cells, the Peclet number is small - diffusion dominates advection. Yet, when the dynamics of concentrated organisms' flagella produce long range chaotic flows, or when assemblies of flagella belonging to large microorganisms produce such flows, the situation changes dramatically. We study this using the model systems of the Volvocales, comprising algae ranging from single cells to those whose surface is covered by thousands of flagellated cells. To apportion the effect of flagellar dynamics between transport and translocation, and to find time resolved correlation between the algae's metabolism and transport rates, is the main objective of our research.

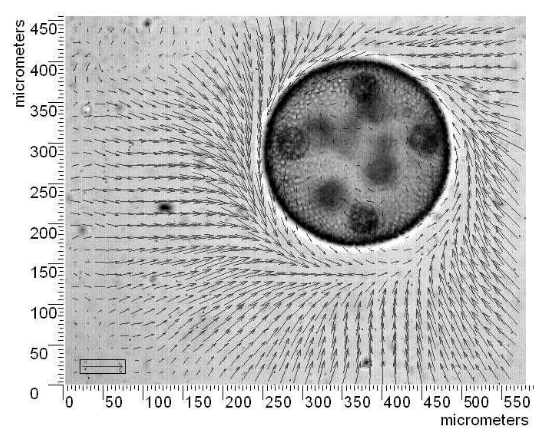

Figure 3: *Fluid velocity field around Volvox carteri, obtained from PIV.*

•"Multicellularity and the Functional Interdependence of Motility and Molecular Transport," C.A. Solari, J.O Kessler, R.E. Goldstein, and R.E. Michod, *preprint* (2005). •"Transport by Collective Flagellar Beating Facilitates Evolutionary Transitions to Multicellularity," M.B. Short, C.A. Solari, S. Ganguly, T.R. Powers, J.O Kessler, and R.E. Goldstein, *preprint* (2005).

Flow-Induced Chirality Transformations of Bacterial Flagella: During the course of bacterial swimming, the multiple rotating helical flagella which are driven by rotary motors embedded in the cell wall undergo complex bundling and unbundling dynamics through episodic reversals of those motors. Many years ago it was determined that motor reversals initiate propagating chirality transformations that move down the length of the flagellum at tens of microns per second. Hotani [J. Mol. Biol. 156, 791 (1982)] investigated this process in detail by subjecting an isolated bacterial flagellum, clamped at one end, to an external fluid flow. He observed that regions of the flagellum transform to the opposite chirality, and travel as pulses down the length of the filament, the process repeating periodically. We have proposed a theory for this phenomenon based on a treatment of the flagellum as an elastic object with multiple stable configurations. The simplest possible implementation of the model accurately reproduces key features seen in experiment. Now we are developing an experiment to study the predictions of this model in more detail as a means of understanding the nanomechanics of flagellar chirality.

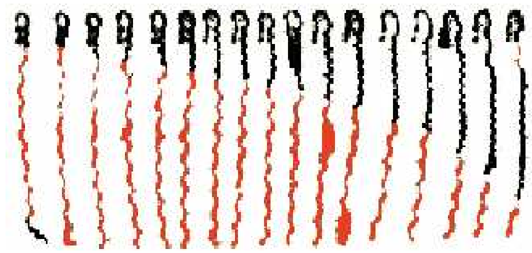

Figure 4: *Dynamics of flow-induced chirality transformations in flagella of Salmonella (Hotani). Time advances left to right, with red (black) representing left-handed (right-handed) domains.*

•"Periodic Chirality Transformations Propagating on Bacterial Flagella," D. Coombs, G. Huber, J.O. Kessler, and R.E. Goldstein, *Phys. Rev. Lett.* **89**, 118102 (2002).

Supercoiling Dynamics of Growing Filaments: Certain bacteria form filamentous colonies when the cells fail to separate after dividing, and those filaments can wrap into complex supercoiled structures as the cells grow. The structures may be solenoids or plectonemes, with or without branches in the latter case. Any microscopic theory of these morphological instabilities must address the nature of pattern selection in the presence of growth, for growth renders the problem nonautonomous and the bifurcations dynamic. We have formulated a general theory for growing elastic filaments with bending and twisting resistance in a viscous medium, and study an illustrative model problem: a growing filament with preferred twist, closed into a loop. Growth depletes the twist, inducing a twisting strain, and closure prevents filament unwinding, leading to supercoils. Growth also induces viscous stresses which can produce buckling. For small intrinsic twist the instability is like Euler buckling, but for large twist it is like the writhing of a twisted filament. Applications to specific biological systems are proposed. Of particular current interest is the possible role of recently-discovered protein filaments with helical morphology along the cell wall of *B. subtilis.*

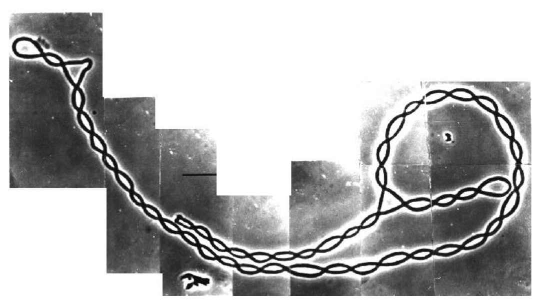

Figure 5: *Supercoiled filament of B. subtilis (Mendelson).*

•"Dynamic Supercoiling Bifurcations of Growing Elastic Filaments," C.W. Wolgemuth, R.E. Goldstein, and T.R. Powers, *Physica D* **190**, 266-289 (2004).

Dynamics of Tendril Perversions: Certain species of climbing vines attach themselves to supports through tendrils which develop helicity after attachment. Often, the tendrils develop regions of opposite helix handedness joined by a junction known as a perversion. A key feature of these structures is that during their development they are elastically imprinted with the shape they display, so that removal of the external constraints leaves them in a nearly equilibrium shape. Existing models based on static elasticity theory can not explain this behavior. We have developed a model in which differential growth and viscoelastic relaxation of the intrinsic curvature and torsion of the filament can explain the details of this phenomenon, in agreement with observations.

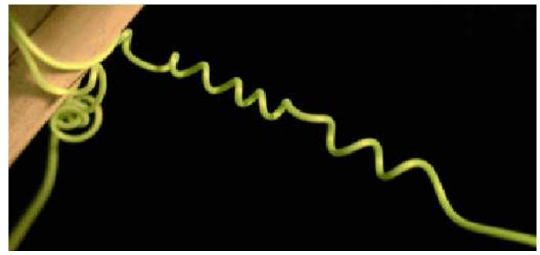

Figure 6: *Tendril perversion in the passion flower.*

•"Buckling Dynamics of Elastoplastic Filaments," R.E. Goldstein and A. Goriely, *in preparation* (2005).

III. Fluid Dynamics & Chemical Pattern Formation

In recent years we have studied certain fluid-dynamical instabilities which were motivated by observations in biophysical contexts, as well as a class of free-boundary problems in pattern formation associated with precipitation. The latter has been a particularly fruitful line of research into the world of geophysics, especially involving the formation of stalactites and related speleothems.

Quantum Necking of Metallic Nanowires: A linear stability analysis of metallic nanowires was performed in the free-electron model using quantum chaos techniques. It is found that the classical instability of a long wire under surface tension can be completely suppressed by electronic shell effects, leading to stable cylindrical configurations whose electrical conductance is a magic number $1, 3, 5, 6, \ldots$ times the quantum of conductance. These results are quantitatively consistent with recent experiments with alkali metal nanowires. When a macroscopic metallic wire is subject to tensile stress, it necks down smoothly as it elongates. We have shown that nanowires with radii comparable to the Fermi wavelength display remarkably different behavior. Using concepts from fluid dynamics, a partial differential equation for nanowire shape evolution is derived from a semiclassical energy functional that includes electron-shell effects. A rich dynamics involving movement and interaction of kinks connecting locally stable radii is found, and a new class of universal equilibrium shapes is predicted.

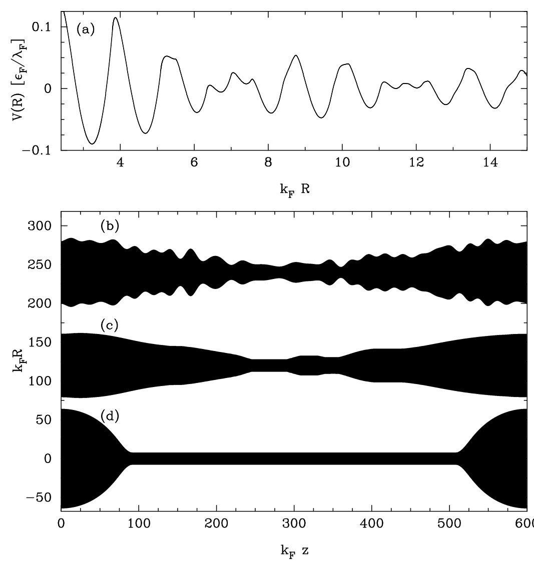

Figure 7: *Electron shell potential for a nanowire as a function of radius, and transient shapes under external tension.*

•"Quantum Suppression of the Rayleigh Instability in Nanowires," F. Kassubek, C.A. Stafford, H. Grabert, and R.E. Goldstein *Nonlinearity* **14**, 167-177 (2001).

•"Quantum Necking in Stressed Metallic Nanowires," J. Bürki, R.E. Goldstein and C.A. Stafford, *Phys. Rev. Lett.* **91**, 254501 (2003).

Coiling, Entrainment and Synchronization of Viscous Fluid Jets: From algal suspensions to magma upwellings and galactic dynamics one finds fluid jets which exhibit complex symmetry-breaking instabilities as they are decelerated by their surroundings. We study the simplest system that captures this complexity yet allows direct experimental control; a saline jet descending through a salinity gradient. The descending jet coils like a corkscrew within a conduit of viscously entrained fluid whose upward recirculation braids the jet. The underlying jet structure and certain scaling relations can be understood through similarity solutions to the fluid equations and the physics of Kelvin-Helmholtz instabilities. The image shows vorticity maps (color) obtained from PIV with suspended microspheres that illustrate the recirculating flow within the conduit in a time-averaged manner (a) and instantaneously (c), and a streak photograph (b) offering another view of the swirling flows that braid the coiling jet. Panels (d,e) and (f,g) show from and side views of two interacting jets that are, respectively, sharing a single conduit and just further apart than a conduit width. In the latter case, the jets synchronize as mirror-images. Panel h reveals that when jets are even further apart they nest together.

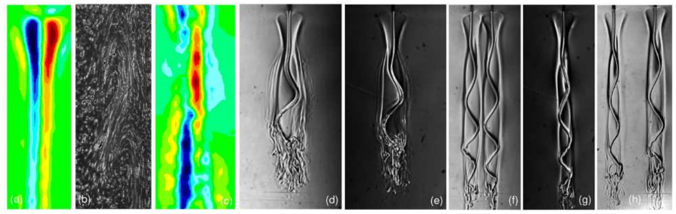

Figure 8: *Flow fields around individual jets, and the interactions between nearby jets.*

•"Inertially driven buckling and overturning of jets in a Hele-Shaw cell," A.I. Pesci, M.A. Porter, and R.E. Goldstein, *Phys. Rev. E* **68**, 056305 (2003).

•"Coiling, Entrainment, and Hydrodynamic Coupling of Decelerated Fluid Jets," C. Dombrowski, B. Lewellyn, A.I. Pesci, J.M. Restrepo, J.O. Kessler, and R.E. Goldstein, *Phys. Rev. Lett.* **95**, 0000 (2005).

Tubular Precipitation and Redox Gradients on a Bubbling Template: Tubular structures created by precipitation abound in nature, from chimneys at hydrothermal vents to soda straws in caves. Their formation is controlled by chemical gradients within which precipitation occurs, defining a surface which templates the growing structure. We report a novel, self-organized periodic templating mechanism producing tubular structures electrochemically in iron-ammonium-sulfate solutions; iron oxides precipitate on the surface of bubbles that linger at the tube rim, then detach, leaving behind a ring of material. The redox gradient spontaneously generated by diffusion of ammonia from the bubble into solution organizes radial compositional layering within the tube wall, a mechanism studied on a larger scale by complex Liesegang patterns of iron oxides formed as ammonia diffuses through a gel containing $FeSO_4$. When magnetite forms within the wall, a tube may grow curved in an external magnetic field.

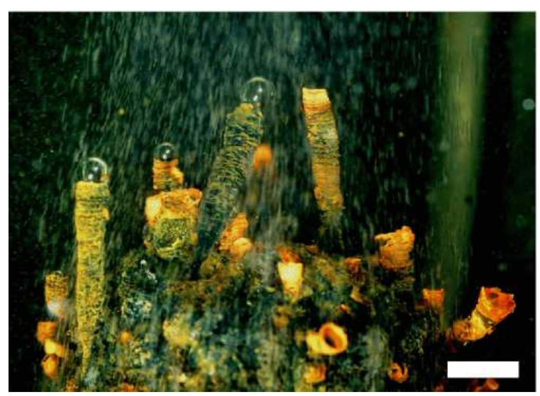

Figure 9: *Ferrotubes growing in solution. Scale bar is 5 mm.*

•"Tubular Precipitation and Redox Gradients on a Bubbling Template," David A. Stone and Raymond E. Goldstein, *Proc. Natl. Acad. Sci. (USA)* **101**, 11537-11541 (2004).

Theory of Speleothem Morphology: The chemical mechanisms underlying the growth of cave formations such as stalactites are well-known, yet no theory has yet been proposed which successfully accounts for the dynamic evolution of their shapes. We have considered the interplay of thin-film fluid dynamics, calcium carbonate chemistry, and CO_2 transport in the cave to show that stalactites evolve according to a novel local geometric growth law which exhibits extreme amplification at the tip as a consequence of the locally-varying fluid layer thickness. Studies of this model show that a broad class of initial conditions is attracted to an ideal shape with the remarkable property of being completely parameter-free, save for an overall scaling, as for the Platonic ideals like the circle and the square. The figure shows three examples of natural stalactites in Kartchner Caverns (Benson, AZ) and the ideal shape which most closely matches them. At the right is a composite average shape (blue, with uncertainties in red) compared with the ideal (black).

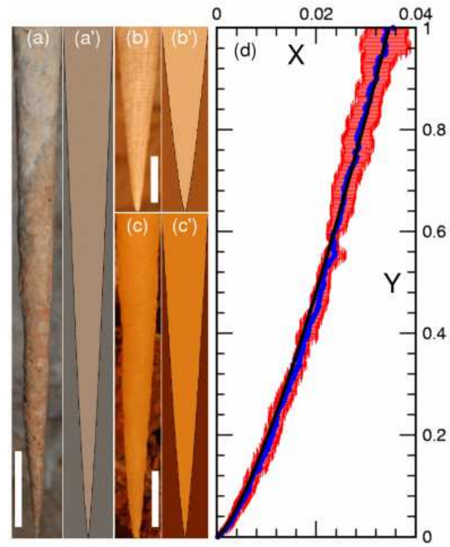

Figure 10: *Individual natural stalactites compared to the Platonic idea, and a statistical comparison.*

•"Stalactite Growth as a Free-Boundary Problem: A Geometric Law and its Platonic Ideal," M.B. Short, J.C. Baygents, J.W. Beck, D.A. Stone, R.S. Toomey, III, and R.E. Goldstein, *Phys. Rev. Lett.* **94**, 018501 (2005). •"Stalactite Growth as a Free-Boundary Problem," M.B. Short, J.C. Baygents, and R.E. Goldstein, *Phys. Fluids* **17**, 083101 (2005).

Tubular Precipitation Around a Fluid Jet: At undersea hydrothermal vents it is common to find long, slender "chimneys" reaching up to tens of meters in height, formed by precipitation at the interface between hot upwelling mineral rich fluid and colder seawater. The growth dynamics of such structures are poorly understood, but center around diffusion of material out from the jet or plume of upwelling fluid, precipitation as those reactants interact with the surrounding fluid, and gradual accretion at the growing rim. In order to study this general class of phenomena in detail, we have developed a model laboratory system capable of control and quantification. A slow jet of aqua ammonia is injected into a solution of iron sulphate, precipitating white rust [$Fe(OH)_2$] at the interface, which slowly transforms to green rust. The dynamics of tube elongation as a function of time at various fluid injection rates are found to obey simple scaling laws which can be understood from a model of high Peclet number flows.

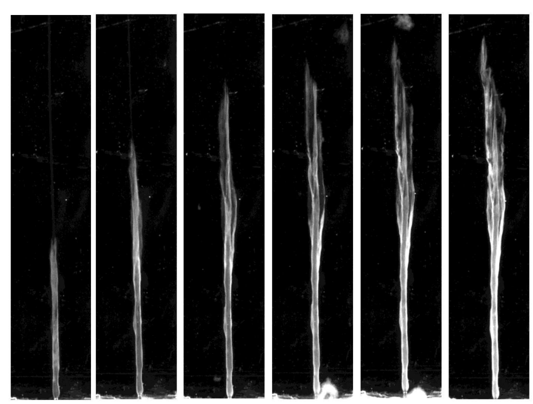

Figure 11: *Growth of iron oxide tubes as a function of time around an injected fluid jet.*

•"Precipitative Growth Templated by a Fluid Jet," D.A. Stone, B. Lewellyn, J.C. Baygents, and R.E. Goldstein, *under review* (2005).

Front Bifurcations and Liesegang Rings in an Oxidation-Reduction System: Liesegang bands are sharp domains of precipitation arranged in a geometric progression, produced by diffusion of a chemical trigger through a porous medium. It has recently been proposed that they arise from an instability of the diffusing front which transforms continuous precipitation into the banded form. We have discovered an experimental system which validates this scenario. In iron sulfate solutions in agar gel, under the influence of diffusing ammonia, precipitation occurs via oxidation-reduction reactions controlled by the ratio Fe(II):Fe(III), and is followed in real time with microprobe measurements of pH and the redox potential, as well as microscopic visualizations. The image shows complex Liesegang patterns that are found in addition to the front bifurcation: a progression of precipitates arranged in an oxidation sequence, from the oxidized orange lepidocrocite at the left to intermediate black magnetite, to the more reduced green rust at the right.

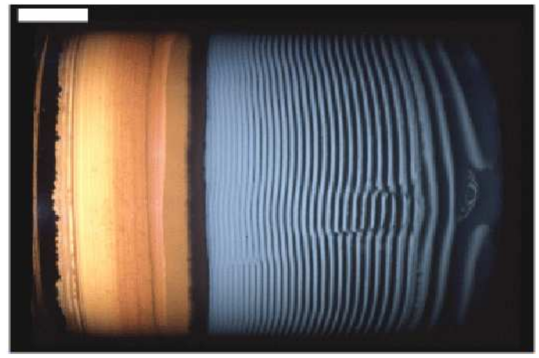

Figure 12: *Liesegang bands in the iron-oxide system. Scale is* 1 *cm.*

•"Front Bifurcations and Liesegang Rings in an Oxidation-Reduction System," D.A. Stone, J.C. Baygents, and R.E. Goldstein, *in preparation* (2005).

IV. Mathematical Physics

We have had a longstanding interest in mathematical problems associated with nonlinear dynamics and pattern formation, including singularity formation during topological transitions and the relation between integrable Hamiltonian systems and the differential geometry of curve motion. Recently, we have explored deep connections between hydrodynamic equations and the foundations of quantum mechanics.

Kinetic Theory, Hydrodynamics, and Quantum Mechanics: Soon after the development of quantum mechanics, Madelung found a mapping from the Schrödinger equation onto a version of Euler's equation. This transformation has a long history, and formed the basis for Bohm' discussion of quantum mechanics based on Hamilton-Jacobi theory. Since fluid dynamical equations can be derived as moments of an underlying kinetic theory, it is natural to wonder whether the quantum hydrodynamics also has an associated kinetic theory. We have shown that this is indeed the case through a mapping onto the Sturm-Liouville operator of the first two balance equations derived from Boltzmann's equation. This irreversible mapping, valid only for a subclass of solutions, is achieved by applying a Fourier transform to the momentum coordinate. In light of this irreversibility, it is necessary to develop a set of consistent prescriptions to find the probability of any physical quantity in the p-conjugate space. These prescriptions coincide with the postulates of quantum mechanics, when the single free parameters of the theory is set equal to Planck's constant. A similar mapping onto the Pauli equation also exists, associated with vortical flow in the hydrodynamic context. The mapping in this case follows a technique common in hydrodynamic problems in which the constraints are expressed in terms of Clebsch variables. We have extended the analysis to the relativistic case, finding mappings onto the Klein-Gordon equation in the irrotational case and to the second-order Dirac equation in the rotational case. Prescriptions for operator symmetrization emerge naturally from this analysis.

•"Mapping of the Classical Kinetic Balance Equations Onto the Schrödinger Equation," A.I. Pesci and R.E. Goldstein, *Nonlinearity* **18**, 211-226 (2005).

•"Mapping of the Classical Kinetic Balance Equations Onto the Pauli Equation," A.I. Pesci, R.E. Goldstein, and H. Uys, *Nonlinearity* **18**, 227-235 (2005).

•"Mapping of the Relativistic Kinetic Balance Equations Onto the Klein-Gordon and Second-Order Dirac Equations," A.I. Pesci, R.E. Goldstein, and H. Uys, *Nonlinearity* **18**, 1295-1304 (2005).

•"Hermitization and Poisson Bracket-Commutator Correspondence as a Consequence of Averaging," A.I. Pesci, R.E. Goldstein, and H. Uys, *under review* (2005).

Goldstein Laboratory

My laboratory is highly interdisciplinary, involving theorists and experimentalists from a wide range of departments and institutions.

Graduate Students

- Luis Cisneros (Physics, PAS 555, `luisc@email.arizona.edu`)
  Biological fluid dynamics - experiment
- Christopher Dombrowski (Physics, PAS 555, `dombrows@email.arizona.edu`)
  Biological fluid dynamics - experiment
- Ryan Krug (Physics, PAS 549, `krug@email.arizona.edu`)
  Granular dynamics - experiment
- Martin B. Short (Physics, PAS 549, `mshort@physics.arizona.edu`)
  Speleothem dynamics, biological physics - theory
- David A. Stone (Soil, Water, and Environmental Science, PAS 541, `dstone@email.arizona.edu`)
  Precipitative pattern formation - experiment

Collaborating Graduate Students

- Cristian A. Solari (Ecology & Evolutionary Biology, `casolari@eeb.arizona.edu`)
  Swimming, stirring, and scaling in Volvox
- Idan Tuval (IMEDEA, Universitat de les Illes Balears, Palma de Mallorca, Spain, `idan@imedea.uib.es`)
  Biological fluid dynamics - theory

Undergraduate Students

- Sujoy Ganguly (Physics, PAS 555, `ganguly1@email.arizona.edu`)
  Volvox flagellar dynamics - experiment
- Chris Smillie (Physics, PAS 555, `smillie@email.arizona.edu`)
  Volvox flagellar dynamics - experiment
- Matti Miranda (Physics, PAS 555, `miranda@physics.arizona.edu`)
  Bacterial flagellar dynamics and optical trapping - experiment
- Braddon Lewellyn (Physics, PAS 549, `iamcyclotron@yahoo.com`)
  Fluid dynamics & precipitative growth - experiment

Collaborating Postdocs

- Jerome Buerki (Physics, `buerki@physics.arizona.edu`)
  Dynamics of nanowires
- Andrew Hausrath (Biochemistry and Molecular Biophysics, `hausrath@email.arizona.edu`)
  Dynamics of protein folding

Current and Recent Faculty Collaborators

- Adriana I. Pesci (Physics, U. of Arizona, pesci@physics.arizona.edu)
  Coiling instabilities of jets, kinetic theory and quantum mechanics
- John O. Kessler (Physics, U. of Arizona, kessler@physics.arizona.edu)
  Jet instabilities, bioconvection, large-scale bacterial coherence, Volvox
- Charles A. Stafford (Physics, U. of Arizona, stafford@physics.arizona.edu)
  Stability and dynamics of nanowires
- J. Warren Beck (Physics, U. of Arizona, wbeck@physics.arizona.edu)
  Speleothem growth, Liesegang bands
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  Jet instabilities, sand ripple dynamics
- Alain Goriely (Math, U. of Arizona, goriely@math.arizona.edu)
  Dynamics of elastic filaments
- Karl Glasner (Math, U. of Arizona, glasner@math.arizona.edu)
  Collective behavior in bacterial dynamics
- James C. Baygents (Chem. & Environ. Eng., U. of Arizona, jcb@maxwell.che.arizona.edu)
  Speleothem growth, precipitative pattern formation
- Joan Curry (Soil, Water, and Environmental Science, U. of Arizona, curry@ag.arizona.edu)
  Speleothem growth, precipitative pattern formation
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  Biological fluid dynamics, spirochete flagella
- Nyles Charon (Cell Biology, U. West Virginia, charon@uwv.edu)
  Spirochete flagella
- Thomas R. Powers (Solid Mechanics, Brown University, thomas_powers@brown.edu)
  Membrane tethers, supercoiling dynamics
- Greg Huber (Physics, UMass Boston, huber@umb.edu)
  Membrane tethers, flagellar polymorphism
- Daniel Coombs (Math, U. British Columbia, coombs@math.ubc.ca)
  Flagellar polymorphism
- Rickard S. Toomey, III (Kartchner Caverns State Park, Benson, AZ, rtoomey@pr.state.az)
  Speleothem morphology

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- Chris H. Wiggins (Ph.D. Physics, Princeton University, 1998)
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- Charles W. Wolgemuth (Ph.D. Physics, University of Arizona, 2000)
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Teaching Interests

I have been teaching as a professor for fourteen years, covering subjects ranging from large introductory physics courses to advanced graduate special-topics courses. As the experimental side of my research has developed, I have also been active in standard undergraduate laboratory courses and have devoted a number of years to the development of a unique graduate biophysics lab course (see below). My teaching philosophy is simple: lecture without notes, emphasize first-principles derivations, dimensional analysis, and intuitive mathematics, and engage the students in problem-solving.

Below is a listing of the courses I have taught (U=undergraduate, G=graduate, U/G=cross-listed).

Biological Physics Laboratory (G)	Advanced Laboratory (U)
Biological Physics (U)	Fluid Dynamics (G)
Solid State Physics (U/G)	Advanced Mechanics (U)
Special Topics in Mechanics (G)	Nonlinear Dynamics and Pattern Formation (G)
Statistical Mechanics (U)	Statistical Mechanics (G)
Introductory Mechanics (U)	Introductory Electricity & Magnetism (U)
Physics for Poets (U)	

In addition to these teaching experiences, at Princeton University and the University of Arizona, I have been a frequent lecturer at the Complex Systems Summer School sponsored by the Santa Fe Institute. As co-director of that school for three years I created a highly-successful laboratory for those students, highlighting table-top experiments in nonlinear science. I have also lectured at various advanced interdisciplinary summer schools, such as the Boulder School on Condensed Matter Physics, a PASI workshop in Bariloche, Argentina, and various schools held at Cargese.

Graduate Interdisciplinary Education in Biological Physics: As one of the five PIs on an NSF IGERT grant awarded in the first year of that program, I had an opportunity to participate in a five-year program of interdisciplinary graduate education at the boundaries between physics, mathematics, and biology. Such a program presents unique challenges for students, faculty, universities, and funding agencies. These challenges range from the pedagogical difficulties of bridging enormously diverse backgrounds to the need for separate departments to recognize such teaching efforts. A central component of that program is a unique graduate laboratory in biological physics for students from backgrounds as diverse as applied mathematics, biomedical engineering, physics, and genetics. In two recent articles we describe in detail how challenges at the various levels have been addressed, including the conceptual bases for the laboratory experiments and the choice of theoretical background material, the course structure, laboratory infrastructure, and details of experimental setups ranging from neuroscience to optical trapping and bacterial pattern formation. These experiences may serve as a guide for universities and departments considering the creation of such interdisciplinary programs.

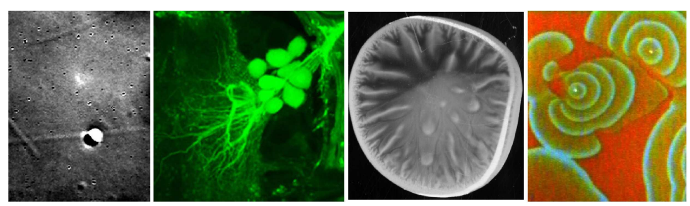

Figure 13: *Experimental themes in the lab course. From left to right: microspheres pulled along microtubules by the motor protein kinesin, fluorescently labelled ganglia in Manduca sexta, bioconvection patterns in a drop of bacterial suspension (Bacillus subtilis), spiral waves in the Belousov-Zhabotinsky system in a petri dish.*

- "Teaching Biological Physics," R.E. Goldstein, P.C. Nelson, and T.R. Powers, *Physics Today* **58**, 46-51 (2005).
- "An Interdisciplinary Graduate Laboratory for Biological Physics," R.E. Goldstein, K. Visscher, R. Reinking, L.A. Oland, and M. Tabor, *in preparation* (2005).