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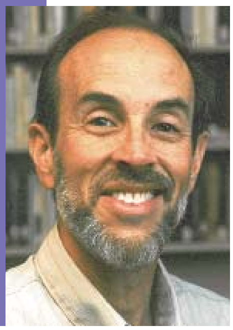

Teaching about fluids

Jerry Gollub

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Fluid physics is rarely discussed more than superficially in undergraduate or graduate physics courses. Yet engagement with the continuum way of thinking about mechanical phenomena can enable students to interpret a wide range of interesting phenomena in geophysics, materials science, engineering, soft-matter physics, biological physics, and complex fluids.[1] (See my column in PHYSICS TODAY, December 2003, page 10.) In this column, I argue that fluid phenomena are accessible and useful to include in introductory courses for a variety of audiences.

In teaching about fluid systems, the use of partial differential equations is not necessarily helpful. Many phenomena—for example, those concerned with interfacial tension and fluid interfaces—are accessible by using simple dimensional reasoning and considering the forces at work on finite fluid elements. The instructor can include novel discoveries from the past decade or two. Doing so can help solve one of the most serious problems with introductory courses: the lack of material reflecting physics as an active, evolving science. Without contemporary examples, physics seems less attractive to some students than do disciplines such as molecular biology.

Fortunately, fluid phenomena are highly visual, entertaining, and accessible to almost any audience through well-designed video demonstrations. Many of them (more than 500) are now readily available on an inexpensive DVD, *Multimedia Fluid Mechanics*, 2nd edition (MFM2), developed by some of the world's experts on fluid dynamics.[1] (I was not personally involved in this project.) Although the developers of this resource especially had in mind engineering education, in which fluid mechanics is widely taught, the DVD is a treasure trove for physics teaching. It also helps many physicists to overcome their lack of experience and therefore feelings of incompetence in teaching about fluid phenomena.

MFM2 can be used in dozens of different ways. I tried some experiments in introductory teaching using a prepublication version. My attempts could certainly benefit from formal evaluation, and I am sure that many PHYSICS TODAY readers could do equally well or better. I encourage you to do your own experimentation.

A short unit on fluid interfaces

My first experiment was to use MFM2 to enrich a typical introductory course for potential physical science majors. Such courses often include a small amount of fluid mechanics, usually limited to a discussion of energy conservation in inviscid fluids (Bernoulli's principle). The instructor generally does not cover the limitation that the principle applies only at high Reynolds number and then only along a streamline. The discussion of fluids in physics courses usually provides no sense of the variety of fascinating phenomena that are easily accessible to visual observation and their prevalence and importance in everyday life.

I focused my effort on a one-week introduction to interfacial fluid phenomena because of the wide range of available examples, including many at the research frontier. Can we afford that much time on such a topic? I think so, because those phenomena are widespread in nature and the benefits to students are significant.

We began by considering some common interfacial fluid phenomena: the wicking of water on a paper towel, the tendency of small droplets to be spherical but to stick to a surface at a particular angle, and the ability of insects to walk on a water surface.

Figure 1. Water strider supported by surface tension and driven by backward transport of momentum. (Courtesy of David Hu and John Bush.)

We discussed the molecular origin of surface tension in terms of the attractive forces between molecules that reduce the energy of a fluid if its interfacial area is made as small as possible; we thus connected surface tension to energy concepts. The surface tension can be estimated as the cohesive energy between two molecules divided by the square of the molecular diameter. The cohesive energy depends on the material but is often at least comparable to the thermal energy kT, so that the surface tension is easily estimated to be a few tens of millijoules per square meter. A video from MFM2 showing the shrinking of a soap film can be used to drive the ideas home.

For a pure nonvolatile fluid in contact with air, the surface tension is fixed, but it can be affected by changing temperature or adding surfactants. As a result, the surface tension is typically nonuniform, which leads to striking dynamical "Marangoni effects" that are easily illustrated visually.

The tendency of droplets to be spherical is most easily seen if the effects of gravity are eliminated by using two immiscible fluids of equal density, as is nicely shown on MFM2. One might also think that a film stretched between two parallel rings would yield a cylindrical surface, but to the surprise of most students, such a surface does not have the minimum area.

Next, I discussed the Laplace equation that relates the pressure difference across a surface to the two local radii of curvature. Although that important result cannot easily be derived at an introductory level, it is simple to illustrate and can easily be shown to explain a host of interesting quasi-static phenomena, including the tendency of a small bubble connected to a large one to shrink, the coarsening of foams, and so on.

A discussion of wetting and contact angles between a fluid and solid would have been logical, but I chose to omit that topic to stay within my one-week time limit. I did discuss the important concept of the capillary length, the scale at which capillary and gravitational forces balance. It can also be derived from dimensional considerations, as I asked students to do in a homework problem. The capillary length is about 3 mm for water, which explains why larger drops are deformed by gravity, why huge drops are found in microgravity situations, and how detergents can cause oil drops to be lifted off a surface. We also considered the phenomenon of capillary rise and the interesting and puzzling question of how trees can grow to a height of 100 m. (See PHYSICS TODAY, January 2008, page 76.)

So far, everything I have mentioned is statics, so it reinforces with nice illustrations the earlier discussions in the introductory course of equilibrium force balances and energetics. What about interfacial dynamics? I decided to limit myself to low Reynolds number, given the time constraints.

The key parameter in low Reynolds number surface-tension-driven dynamics is the capillary number, a dimensionless quantity that gives the relative importance of surface tension and viscosity. An important example is the Rayleigh–Plateau instability, which causes a slow flow from a faucet to break up. The capillary number also governs how fast a fluid deposited on a surface will spread—for example, in spin coating during microfabrication.

I enjoyed mentioning some examples from the current research literature, which is surveyed beautifully in MFM2 by Marc Fermigier, David Quéré, and Christophe Clanet. Examples include studies of insects on a fluid surface by John Bush and his collaborators[2] (figure 1) and the work of Neil Gershenfeld and his collaborators (figure 2) showing how digital logic can be implemented in a microfluidic device by manipulating bubbles.[3] After seeing the bubble logic, one of my students came to my office and said, "Although I was thinking of not continuing in physics next semester, after seeing the bubble logic, I really have to take the second semester." My limited experience at least suggests the

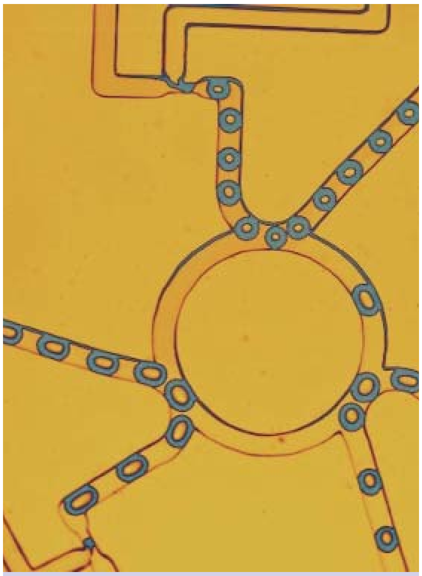

Figure 2. Logic gates implemented using microfluidic channels and bubbles. (Courtesy of Manu Prakash and Felice Frankel.)

potential for bright students to notice and respond to seeing contemporary research in introductory physics.

More than 80 examples of recent discoveries involving interfacial fluid phenomena are presented on MFM2 as short videos, with brief explanations and references to the literature. They are absolutely fascinating: unstable interfaces, dynamics of drops and bubbles, singularities, and so on. There is far more material than can be used in class, but it would be great for students to peruse. Next time, I will purchase some copies and mount MFM2 in our computer lab for students to explore, in conjunction with some homework questions. Practically any PHYSICS TODAY reader, even those who will not use the material for teaching, would have a stimulating time exploring MFM2. Other parts of the DVD that focus on more engineering-oriented fluid dynamics topics such as boundary layers and turbulence may be less applicable to physics teaching, but they are also worth a serious look by instructors and students.

Some will feel that the material I have discussed is appropriate only for courses aimed at strong students who are potential physics majors. Such students can more easily afford the tradeoff between novel topics and the more traditional mechanics because many have already studied mechanics in AP physics courses. On the other hand, interfacial phenomena and other fluid topics are relevant for students who are more interested in biology and medicine than physics, so I would find a way to use the DVD with those students too.

Fluids for nonscience majors

I have also taught fluid topics in a course I called Living in a Fluid World, aimed at students meeting a science distribution requirement. More than half of the course is devoted to showing how biological organisms have adapted to a fluid environment, including swimming, flight, circulatory systems, and transport by advection and diffusion. Again, MFM2 is valuable in providing real-world examples to illustrate the principles. All the basic ideas of mechanics are well illustrated in such a course, which was stimulated by Steven Vogel's book *Life in Moving Fluids.*[4]

I especially like teaching nonscience majors because I can select almost anything I find interesting, such as propulsion at low Reynolds number or the forces governing winds in cyclones in the northern and southern hemispheres. Furthermore, it is straightforward to use fluid examples to show the power of simple arguments based on estimates and dimensional reasoning.

In addition to short weekly quantitative assignments, I generally ask for a modest research paper or a photographic project on a topic of the student's choice. Some of the papers turn out to be quite interesting: drafting in bicycle racing, fluid dynamics of sailing, the thermohaline ocean circulation, lava flows, and so on. I can provide more details about the course on request.

The single largest difficulty I have encountered in incorporating fluid mechanics into introductory physics courses is that standard textbooks do a poor job in covering fluids. However, MFM2 goes a long way toward mitigating that difficulty. Of course, it would be a good idea to use live demonstrations as well as video resources, if time permits.

I appreciate the financial support of NSF's division of materials research.

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