spiral revolutions";[3] that remarkable result, however, has been ignored.

Considerable evidence exists that Newton's early theory of orbital motion was based on the mathematical description of curvature that he and, independently, Christiaan Huygens had developed. However, Newton's approach, based on a decomposition of motion along the tangent and along the normal to the orbital curve, was missing an essential ingredient. Newton was not yet aware that for central forces, angular momentum is conserved, and thus Kepler's second law (area law) is justified.

Newton later admitted that, in 1679, "in answer to a letter to Dr. Hook . . . I found now that whatsoever was the law of the forces which kept the Planets in their Orbs, the areas described by the Radius drawn from them to the Sun would be proportional to the times in which they were described."[4] What Hooke had suggested to Newton is that orbital motion could be decomposed into "a direct [inertial] motion by the tangent, and an attractive motion [radial] towards the central body."[4] For a central impulsive force acting at periodic intervals, this decomposition of motion makes the conservation of angular momentum self-evident, as Newton subsequently showed in *De Motu*. His proof became a cornerstone of the *Principia*, because it allowed him to geometrize orbital dynamics by replacing the time variable by the area swept by the radial line drawn to the center of force.

Contrary to Gal's argument that Hooke's scientific style was "radically different from Newton's," and Smith's assertion of a "monumental contrast" between their approaches to science, both Hooke and Newton had a very similar and quite modern approach, based on observations and experiments, to the understanding of natural phenomena. For example, Hooke reached his views of planetary motion by analyzing the motion of a conical pendulum, as he explained in detail in a 1666 lecture given at the Royal Society of London.[4]

In his review, Smith states that "the great value of Gal's book lies in his analysis of how Hooke arrived at his conception [of orbital motion] through his research in optics." But in his Royal Society lecture, Hooke explicitly rejected the optical analogy that the "ending" of the motion of planets into a curve is caused by the "unequal density of the medium." The essential difference in their approaches is that Newton was able to translate physical concepts into mathematical form and solve the resulting equations, while Hooke lagged far behind in that ability. The theory of planetary motions was not "divined" by Newton, but should be recognized as a remarkable joint scientific achievement of Newton and Hooke.

References

1. O. Gal, *Meanest Foundations and Nobler Superstructures: Hooke, Newton and the "Compounding of the Celestiall Motions of the Planetts,"* Kluwer Academic, Boston (2003), p. 184.
2. Ref. 1, p. 188.
3. M. Nauenberg, *Arch. Hist. Exact Sci.* **46**, 221 (1994); J. B. Brackenridge, M. Nauenberg, in *The Cambridge Companion to Newton*, I. B. Cohen, G. E. Smith, eds., Cambridge U. Press, New York (2003), p. 85.
4. M. Nauenberg, *Am. J. Phys.* **62**, 331 (1994).

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Science Miseducation in *A Private Universe*

In discussing the important question of why physics understanding is so poor, Rustum Roy mentions the Annenberg Project video *A Private Universe*[1] and expresses his conclusion that "less than 10% of the American populace can handle any kind of abstraction" (PHYSICS TODAY, August 2003, page 10). I also recommend the video, but for the opposite reason. After my first viewing, I felt about it as Roy does, but after additional viewings (including a very recent refresher), I suggest we consider the possibility that the culprit is inadequate teaching, not "incapable" students.

Perhaps the sharpest image that first-time viewers of the video come away with is ninth-grade Heather's insistence that the light from the Sun in winter does not go directly to Earth but instead bounces toward Earth at a sharp angle, somewhere out in space. A private universe indeed!

The film should be viewed several times. Initially, Heather had had no instruction at all in astronomy. Before the second round of filming, she received instruction, including diagrams, on summer (light striking Earth at 90°, which, by the way, it never does at her northern latitude) and winter (light striking obliquely). Her teacher told her that in winter, the light is "indirect." My guess is that the instructor, unfortunately, wanted to avoid using the word "oblique" as being too technical.

Almost anyone in our society knows what indirect lighting is. If the room you are in is illuminated by indirect lighting, you don't see the source of the light at all; what you see is only light that has bounced off something at a sharp angle, and from there has proceeded to your eye (directly or indirectly). Heather is most likely just trying to integrate her correct understanding of indirect lighting with the instructor's insistence that winter sunlight is indirect.

That exercise provides no support at all for the idea that Heather is incapable of handling abstraction. I urge that any such sweeping and consequential conclusion be established in a peer-reviewed education journal before it is otherwise disseminated to the physics community.

A fundamental reason why physics education is in such poor shape is typified by Michael Riordan's Opinion piece in the same issue of PHYSICS TODAY (page 50). Although I absolutely agree with Riordan's insistence on experimental testing of theories, his emphasis on the nonexistent (in physics) distinction between things that are "real" and things that are purely "mathematical" is wrong. We know from quantum mechanics that nothing is real, except for the observations themselves.

Reference

1. Annenberg Project, *A Private Universe*, available for viewing online at http://www.learner.org/resources/series28.html.

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Roy replies: Richard Henry's letter is so incredibly ambivalent that I find that his own last paragraph, which comments on Michael Riordan, could form my rejoinder to his first section. "We [meaning physicists] know from quantum mechanics that nothing is real except for the observations themselves."

I urge every reader to "observe" the Annenberg film for themselves via the Web site provided in Henry's letter. My observations of high-school and college students (including 50-plus years of hundreds of graduate students) from all disciplines are that direct observation using as many of the human senses as possible is the only way by which learning sticks for the vast majority of Americans. Professionals in the more abstract sciences should accept the fact that their fellow citizens haven't a clue what all those weird equations mean, will never use them, and basically couldn't care less.

Pity the poor abstract theologians, who have had the same problem for millennia. Religious leaders were a different breed. They never used abstractions; they just told real life stories (for example, Jesus' rabbinical parables on the good Samaritan or the prodigal son, or the battle stage in the Hindu epic *Mahabharata*).

If physicists want citizens to learn science, they should start with things the average citizen can observe repeatedly with as many senses as possible—especially touch.

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Riordan replies: The question of what is "real" has been debated—and will continue to be debated—by philosophers for centuries. If nothing is real except for observations, as Richard Henry states in his last sentence, then quantum mechanics itself must not be real or true. Therefore, his strict empiricist conclusion rests on very shaky ground.

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SQUIDs Remain Best Tools for Measuring Brain's Magnetic Field

The uninformed reader might be misled into believing that optical magnetometers (see PHYSICS TODAY, July 2003, page 21) will soon displace SQUIDs for biomagnetic measurements. I have spent 30 years using superconducting quantum interference device (SQUID) magnetometers and miniature induction-coil magnetometers to measure biomagnetic fields with ever-increasing spatial resolution. Several significant obstacles lie between optical magnetometers and high-resolution measurements of the brain's magnetic field.[1]

Several points are worthy of careful analysis. First, the typically reported sensitivity of SQUIDs, 1 fT/Hz$^{1/2}$, is not a fundamental limit set by the Josephson effect, but a practical one. One must consider thermal (Johnson and thermoelectric) noise within the Dewar flask and the object being studied; the object's intrinsic noise—for example, brain noise (thermal currents and background neural activity within the brain); fluctuations of magnetic shields; environmental magnetic noise; the desired spatial resolution; and the dynamic range of the electronics. SQUID sensitivities of nearly 10^{-17} T/Hz$^{1/2}$ have been reported.[2] With the exception of SQUID microscopy, more sensitive SQUIDs are not generally needed for biomagnetism, because the existing ones have reached the noise floor set by the Dewar, the object being studied, or the environment.

Because superconducting pickup coils can either trap or exclude magnetic flux, SQUIDs have the tremendous advantage of being able to measure femtotesla magnetic fields in the presence of tesla-strength steady fields and microtesla time-varying ones. A well-balanced SQUID gradiometer operating in the geomagnetic field can achieve a common mode rejection of up to 10^7. Electronic gradiometry allows high-quality SQUID recordings of the adult and fetal magnetoencephalogram (MEG) in unshielded laboratories.[3]