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More thoughts on physics pedagogy FREE

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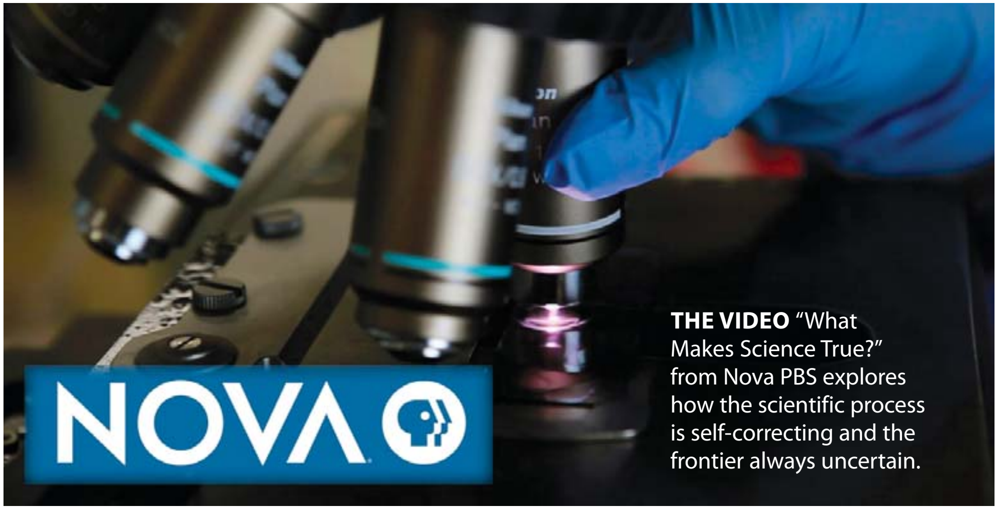
Science's endangered reputation

For many people, science is no longer an indisputable enterprise that builds knowledge and defines the progress of our society. Highly publicized cases of scientific misconduct, misrepresentation or oversimplification by the media, and the low reproducibility of research results have created an impression that science in general cannot be trusted. A YouTube video with the title "Is There a Reproducibility Crisis in Science?" has more than 300 000 views, "Is Science Reliable?" has more than 400 000, and "Is Most Published Research Wrong?" has more than 2.4 million; other online publications and videos with similar titles abound. For comparison, the NOVA PBS video "What Makes Science True?," which explains the ability of science to eventually correct misleading results, has only 39 000 views on YouTube.



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THE VIDEO "What Makes Science True?" from Nova PBS explores how the scientific process is self-correcting and the frontier always uncertain.

Scientific research does not take place in a vacuum; it is directly connected to the politics of society because most research is funded with taxpayers' dollars. The general public and members of the US Congress are increasingly asking, Why should money be wasted on unreliable and, consequently, useless research?

Scientific misconduct has been discussed extensively by federal funding agencies, and in 2000 the White House Office of Science and Technology Policy adopted a specific definition for research misconduct to be applied across all government agencies. According to that definition, research misconduct means "fabrication, falsification, or plagiarism (FFP) in proposing, performing, or reviewing research, or in reporting research results." A published analysis of data on FFP and the reproducibility of research results shows that although physics and related sciences are definitely not immune, they fare better than biology, medicine, psychology, and other branches of science.[1–5]

The most likely reasons for that difference are that physics is a quantitative science and is governed by a set of major laws. So, it is especially sad to see some research papers include statements and conclusions that directly violate those laws and misuse scientific terminology. For example, I know of papers reporting solar cells, LEDs, photodetectors, and other devices with efficiency over 100%. Interestingly, soon after those results were published came new reports that claimed 250%, 60 000%, and even higher efficiency.

An important question is, What separates good science from bad—is it a narrow line or a gray area? These days, one can find physics and engineering papers stating that a presented result, approach, or method "has opened the door for a revolutionary device design," or "offers an unmatched portfolio of properties," or "leads to fabrication strategies not possible with traditional technology," or "will find use in widespread technological applications," and so forth. Definitely, such statements cannot be considered FFP. At the same time, they cannot be proven. Many of my colleagues consider exaggerations and overstatements to be a first step into the gray area that separates honest science from everything else.

Physical constants are universal; it does not matter when, how, or by whom measurements and calculations were performed, as long as they were performed and reported correctly. Similarly, scientific definitions are useful only if they have been applied properly, and any deviation from the established norm should at least be explained. Overstatements, misuses of scientific definitions, and exaggerations of research results, often due to the pressure to publish and the competition for funding, do not fall under the umbrella of FFP. Nevertheless, they do harm the reputation of science (as well as the reputation of the authors) and should not be tolerated by the reviewers and editors of research journals.

It is well known that reputation is hard to build and easy to lose; however, it is even harder to rebuild. We still have a chance to rebuild the reputation of science, but we have to start as soon as possible.

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More thoughts on physics pedagogy

John Winfrey's thought-provoking letter in PHYSICS TODAY's April 2020 Readers' Forum (page 10) makes two points regarding the physics curriculum and teaching materials. First, he notes that gaps in understanding originate in the undergraduate curriculum and persist into faculty teaching; second, he suggests that they are part of a problem with physics textbooks and pedagogy not adhering to well-known discoveries in cognitive science.

Gaps are not a problem in just the physics curriculum; they are pervasive throughout undergraduate education. One of us (Kevin) has taught the mathematics sequence from college algebra through differential equations and has seen the problem most clearly exhibited in trigonometry courses. Despite its elementary nature, trigonometry is an important recruiting ground for physical-sciences and engineering students: Class rosters are filled with students who show mathematical and scientific talents but have had poor guidance about how to apply them.

A typical trigonometry course is divided into three parts: trigonometric ratios and functions; analytic trigonometry, with its identities and equations; and applications and advanced topics. The courses tend to overemphasize part two, with classes wallowing for week after week in identities. As a result, advanced topics such as complex numbers, polar coordinates, and vectors aren't covered at all, and an opportunity to introduce concepts that physical scientists and engineers use extensively is squandered. Similarly, algebra courses will skip important material later in the textbook, such as an introduction to exponential and logarithm functions, because of lack of time. In a differential equations course, operational mathematics might be skipped.

In physics classes, instructors may eliminate topics such as hydrostatics or some of the introduction to fields—especially quantities related to the magnetic field—to make room for advanced topics that may be of more interest to faculty and students but actually do most students little good. Moreover, introductory courses in physics and in engineering will present vectors in somewhat different ways. Mechanical engineering students may not even take Physics I because the material is ostensibly covered in their statics and dynamics courses. So various cohorts of students entering Physics II possess different ideas and tools.

Winfrey posits that gaps in understanding result from instructors' attempts to build from specific to general ideas, and because of time constraints in most courses, the students never reach the general material. That approach, he writes, ignores the primacy effect: Material presented earlier is mastered better than material presented later. Textbook authors should therefore take the primacy effect into account and go from broad, general concepts to specifics.

Winfrey's suggestion runs into the somewhat unsettled realm of educational theory. Every teacher recognizes that students learn early course material best, but it isn't clear why. Many theories, all with some supporting evidence, attempt to explain the effect. For example, some researchers propose that information is easier to retrieve when it is subjected to occasional tests of recall, and early course content is tested more often.[1,2] Another theory holds that later course content exceeds the cognitive load that students are able to successfully process and store in their long-term memory.[3]

An introductory physics course will seek to teach students the foundations of electrostatics, in which time derivatives are zero. Winfrey's more general formulation of Coulomb's law brings in dynamical quantities. Although that formulation is in keeping with his general-to-specific paradigm, it runs counter to the idea of reducing unnecessary complexity in order to avoid cognitive overload.

Whatever the true sources of cognitive barriers in instruction turn out to be, all of us who teach mathematics, physics, and engineering can do better by learning what our customers—the students—need most and reordering or reemphasizing instruction to meet those needs. Possibly we can add big-picture generalizations, as Winfrey suggests, while also removing redundant material to avoid adding to the cognitive load. It is our responsibility as instructors to determine, in coordination with other departments, what is germane for each course we teach and to design our instruction accordingly.

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A footnote on the founding of NSF

Emily Gibson's article "NSF and postwar US science" (PHYSICS TODAY, May 2020, page 40) was an enjoyable read. I have a personal footnote to add.

In 1954, as a graduating senior at the University of Wisconsin–Madison, I had been interested in solar astronomy even though I was majoring in physics. Joseph Hirschberg, Newell Mack, and I took a laboratory slate tabletop and other equipment to Mellen, Wisconsin, to observe an eclipse.

Although we did not get the information we wanted during that eclipse, another one was going to occur in the South Pacific in 1958. Groups from the High Altitude Observatory, the Sacramento Peak Observatory, and other facilities were planning to go there with support from the US Navy.

Julian Mack, who had been my senior thesis adviser, suggested that I write a proposal. He signed it, sent it to the Office of Naval Research (ONR), and then went off for an appointment as a scientific attaché in Sweden.

I received a letter from the ONR that they no longer provided general scientific support for the study of solar eclipses. But a new federal agency, the National Science Foundation, now handled such proposals, and the ONR forwarded my request. A while later I received a letter from NSF that included a check to fund the trip.

I took the check to the department chair, Ragnar Rollefson, who said he would have an account opened so that I could spend funds for equipment and travel. Time was short to have equipment dockside at Naval Base San Diego for the navy to take it to Pukapuka, New Zealand, via Honolulu. So I asked George Streander, Mack's instrument maker, if he would sign on and help make the equipment to study the eclipse. I designed an observation hut and gave lumber estimates to the navy, which would get the wood in Hawaii. I also designed the optics and heliostat; George made castings and all the fine parts, and he suggested bearings and a drive system for the heliostat. Narrow band-pass filters, lenses, photographic plate holders, tools, and other items were ordered and purchased. The university carpentry shop made the boxes for the equipment, and we took