

In Praise of Hard Questions

Great cases, as U.S. Supreme Court Justice Oliver Wendell Holmes suggested a century ago, may make bad law. But great questions often make very good science.

Unsolved mysteries provide science with motivation and direction. Gaps in the road to scientific knowledge are not potholes to be avoided, but opportunities to be exploited.

“Fundamental questions are guideposts; they stimulate people,” says 2004 Nobel physics laureate David Gross. “One of the most creative qualities a research scientist can have is the ability to ask the right questions.”

Science’s greatest advances occur on the frontiers, at the interface between ignorance and knowledge, where the most profound questions are posed. There’s no better way to assess the current condition of science than listing the questions that science cannot answer. “Science,” Gross declares, “is shaped by ignorance.”

There have been times, though, when some believed that science had paved over all the gaps, ending the age of ignorance. When *Science* was born, in 1880, James Clerk Maxwell had died just the year before, after successfully explaining light, electricity, magnetism, and heat. Along with gravity, which Newton had mastered 2 centuries earlier, physics was, to myopic eyes, essentially finished. Darwin, meanwhile, had established the guiding principle of biology, and Mendeleev’s periodic table—only a decade old—allowed chemistry to publish its foundations on a poster board. Maxwell himself mentioned that many physicists believed the

trend in their field was merely to measure the values of physical constants “to another place of decimals.”

Nevertheless, great questions raged. Savants of science debated not only the power of natural selection, but also the origin of the solar system, the age and internal structure of Earth, and the prospect of a plurality of worlds populating the cosmos.

In fact, at the time of Maxwell’s death, his theory of electromagnetic fields was not yet widely accepted or even well known; experts still argued about whether electricity and magnetism propagated their effects via “action at a distance,” as gravity (supposedly) did, or by Michael Faraday’s “lines of force” (incorporated by Maxwell into his fields). Lurking behind that dispute was the deeper issue of whether gravity could be unified with electromagnetism (Maxwell thought not), a question that remains one of the greatest in science today, in a somewhat more complicated form.

Maxwell knew full well that his accomplishments left questions unanswered. His calculations regarding the internal motion of molecules did not agree with measurements of specific heats, for instance. “Something essential to the complete state of the physical theory of molecular encounters must have hitherto escaped us,” he commented.

When *Science* turned 20—at the 19th century’s end—Maxwell’s mentor William Thomson (Lord Kelvin) articulated the two grand gaps in knowledge of the day. (He called them “clouds” hanging over physicists’ heads.) One was the mystery of specific heats

that Maxwell had identified; the other was the failure to detect the ether, a medium seemingly required by Maxwell’s electromagnetic waves.

Filling those two gaps in knowledge required the 20th century’s quantum and relativity revolutions. The ignorance enveloped in Kelvin’s clouds was the impetus for science’s revitalization.

Throughout the last century, pursuing answers to great questions reshaped human understanding of the physical and living world. Debates over the plurality of worlds assumed galactic proportions, specifically addressing whether Earth’s home galaxy, the Milky Way, was only one of many such conglomerations of stars. That issue was soon resolved in favor of the Milky Way’s nonexclusive status, in much the same manner that Earth itself had been demoted from its central role in the cosmos by Copernicus centuries before.

But the existence of galaxies outside our own posed another question, about the apparent motions of those galaxies away from one another. That issue echoed a curious report in *Science*’s first issue about a set of stars forming a triangular pattern, with a double star at the apex and two others forming the base. Precise observations showed the stars to be moving apart, making the triangle bigger but maintaining its form.

“It seems probable that all these stars are slowly moving away from one common point, so that many years back they were all very much closer to one another,” *Science* reported, as though the four stars had all begun their journey from the same place.

Copernicus
Maxwell
Mendeleev

Understanding such motion was a question “of the highest interest.”

A half a century later, Edwin Hubble enlarged that question from one about stellar motion to the origin and history of the universe itself. He showed that galaxies also appeared to be receding from a common starting point, evidence that the universe was expanding. With Hubble’s discovery, cosmology’s grand questions began to morph from the philosophical to the empirical. And with the discovery of the cosmic microwave background in the 1960s, the big bang theory of the universe’s birth assumed the starring role on the cosmological stage—providing cosmologists with one big answer and many new questions.

By *Science*’s centennial, a quarter-century ago, many gaps still remained in knowledge of the cosmos; some of them have since been filled, while others linger. At that time debate continued over the existence of planets around faraway stars, a question now settled with the discovery of dozens of planets in the solar system’s galactic neighborhood. But now a bigger question looms beyond the scope of planets or even galaxies: the prospect of multiple universes, cousins to the bubble of time and space that humans occupy.

And not only may the human universe not be alone (defying the old definition of universe), humans may not be alone in their own space, either. The possible existence of life elsewhere in the cosmos remains as great a gap as any in present-day knowledge. And it is enmeshed with the equally deep mystery of life’s origin on Earth.

Life, of course, inspires many deep questions, from the prospects for immortality to the prognosis for eliminating disease. Scientists continue to wonder whether they will ever be able to create new life forms from scratch, or at least simulate life’s self-assembling capabilities. Biologists, physicists, mathematicians, and computer scientists have begun cooperat-

ing on a sophisticated “systems biology” aimed at understanding how the countless molecular interactions at the heart of life fit together in the workings of cells, organs, and whole animals. And if successful, the systems approach should help doctors tailor treatments to individual variations in DNA, permitting personalized medicine that deters disease without inflicting side effects. Before *Science* turns 150, revamped versions of modern medicine may make it possible for humans to live that long, too.

As *Science* and science age, knowledge and ignorance have coevolved, and the nature of the great questions sometimes changes. Old questions about the age and structure of the Earth, for instance, have given way to issues concerning the planet’s capacity to support a growing and aging population.

Some great questions get bigger over time, encompassing an ever-expanding universe, or become more profound, such as the quest to understand consciousness. On the other hand, many deep questions drive science to smaller scales, more minute than the realm of atoms and molecules, or to a greater depth of detail underlying broad-brush answers to past big questions. In 1880, some scientists remained unconvinced by Maxwell’s evidence for atoms. Today, the analogous debate focuses on superstrings as the ultimate bits of matter, on a scale a trillion trillion times smaller. Old arguments over evolution and natural selection have descended to debates on the dynamics of speciation, or how particular behaviors, such as altruistic cooperation, have emerged from the laws of individual competition.

Great questions themselves evolve, of course, because their answers spawn new and better questions in turn. The solutions to Kelvin’s clouds—relativity and quantum physics—generated many of the mysteries on today’s list, from the composition of the cosmos to the prospect for quantum computers.

Ultimately, great questions like these both

define the state of scientific knowledge and drive the engines of scientific discovery. Where ignorance and knowledge converge, where the known confronts the unknown, is where scientific progress is most dramatically made. “Thoroughly conscious ignorance,” wrote Maxwell, “is the prelude to every real advance in science.”

So when science runs out of questions, it would seem, science will come to an end. But there’s no real danger of that. The highway from ignorance to knowledge runs both ways: As knowledge accumulates, diminishing the ignorance of the past, new questions arise, expanding the areas of ignorance to explore.

Maxwell knew that even an era of precision measurements is not a sign of science’s end but preparation for the opening of new frontiers. In every branch of science, Maxwell declared, “the labor of careful measurement has been rewarded by the discovery of new fields of research and by the development of new scientific ideas.”

If science’s progress seems to slow, it’s because its questions get increasingly difficult, not because there will be no new questions left to answer.

Fortunately, hard questions also can make great science, just as Justice Holmes noted that hard cases, like great cases, made bad law. Bad law resulted, he said, because emotional concerns about celebrated cases exerted pressures that distorted well-established legal principles. And that’s why the situation in science is the opposite of that in law. The pressures of the great, hard questions bend and even break well-established principles, which is what makes science forever self-renewing—and which is what demolishes the nonsensical notion that science’s job will ever be done.

—TOM SIEGFRIED

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Darwin

Newton

Hubble

Kelvin