

Commentary

Unity of physics perhaps not as grand as once thought

Most graduate physics departments have a qualifying exam that requires every graduate student to be well versed in all of basic physics—classical mechanics, quantum mechanics, statistical physics, electrodynamics, and other core areas—at a fairly advanced level. Here at the University of Maryland, for example, during two grueling four-hour sessions, graduate students had to answer five quantum problems and five classical problems with no options from which to choose. Requiring students to have such all-encompassing expertise merely to begin their thesis research is essentially unthinkable in chemistry, biology, mathematics, computer science, and other disciplines.

Implicit in broadly imposing such an exam is the dogma that physics is a unified pursuit. But how real is that unity of physics for today's practicing research physicists? More importantly, is it still relevant for truly cutting-edge studies?

I do not know of anyone who reads even the titles of all the papers published in *Physical Review Letters*, let alone the actual papers. Although some physicists, including me, have published in multiple *Physical Review* journals, they do so more from the multidisciplinary nature of certain research activities than from a deep intrinsic correlation among subdisciplines.

Of course, physics has unifying themes rooted in classical mechanics, quantum mechanics, statistical physics, and electrodynamics, and even more so in the shared language of mathematics: Much of physics is described by partial differential equations, integrals, linear algebra, and so on. One could also say that symmetry principles and conservation laws provide the underlying unification for physics, but they are quite broad and are equally operational in biology and chemistry. If they are all we have to connect all of physics, I am quite underwhelmed. "Unity" should mean more than just the common language of mathematics and the correlation of subjects—



Sankar Das Sarma, author of this commentary, is a physics faculty member at the University of Maryland in College Park.

quantum mechanics, for example—that were already well developed by the 1930s.

When Isaac Newton integrated terrestrial and celestial mechanics by realizing that the same laws of inertia and gravitational forces control phenomena in the cosmos and on Earth, the unity of physics was manifestly obvious at a grand scale. In fact, I consider Newton's unification of the two disciplines to be the greatest leap in theoretical science ever; only Charles Darwin's theory of natural selection comes even close. Similarly,

James Clerk Maxwell's unification of electricity and magnetism did not have to be announced; it was manifest.

Although it was a tremendous theoretical unification, Albert Einstein's insight that gravity and inertia are the same already has a much weaker unifying effect, compared with Newton's or Maxwell's, on various research areas of physics today. For example, condensed-matter physics, my chosen field of research, is essentially unaffected directly by general relativity. I find general relativity to be extremely beautiful, but I last

had any direct contact with it in my beginning graduate year, more than four decades ago, when I decided to learn it on my own by studying Steven Weinberg's wonderful book on the subject, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity* (1972).

I do not believe that my in-depth graduate study of general relativity has had any more effect on my condensed-matter physics research than has my studying Jean-Paul Sartre's existential treatise *Being and Nothingness* in the early 1970s. Physics is now far too specialized for a theory to have any unifying effect on another part of physics just by virtue of its mathematical elegance. General relativity is extremely mathematically beautiful and is truly a grand theory, but that does not make it particularly relevant for understanding magnets or superconductors or transistors in any direct sense!

The standard model is the great paradigmatic success of the past 50 years of particle physics. But one could do outstanding work in condensed matter—and many do—without knowing anything about quarks. String theory, the purported Theory of Everything, has had little direct effect on condensed-matter physics regardless of the many speculative and brilliant suggestions on its possible role in condensed-matter phenomena. Theorists have used string dualities to produce many abstract answers in the field, but unfortunately, what the corresponding questions are (and why anyone should care) remain unclear.

One may argue that quantum field theory has been the unifying theme in physics over the past 70 years. That is partially correct for particle and condensed-matter physics. Quantum electrodynamics, the renormalization group, and topological quantum field theories

provide a common language for many topics in condensed-matter and particle physics, but in vast areas of those fields, quantum field theories play no role whatsoever.

Much of materials physics, the most active branch of condensed-matter physics, is interpreted primarily in terms of mean-field band-structure theories, and the most cited papers in all of physics are all band-structure theories. Quantum field theory is essentially irrelevant to their practice and success. Once the quantum nature of photons is incorporated, most of atomic physics is also generally independent of quantum field theories. And, of course, substantial branches of physics—plasmas, fluids, soft matter, and biophysics, for example—are independent of quantum physics for all practical purposes.

I can go further. General unifying themes have not been particularly successful in either predicting or explaining the great experimental discoveries of condensed-matter physics. For example, there is nothing particularly beautiful or unifying about cuprates like lanthanum strontium copper oxide (LSCO) or yttrium barium copper oxide (YBCO) except that they are where high-temperature superconductivity was discovered through serendipity. Although there is an elegant and well-accepted long-wavelength topological quantum field theory for quantum Hall effects in which the boundary-bulk correspondence is fundamental, experiments have so far failed to establish that correspondence decisively.

Developments in physics, unlike in math, are not necessarily logical, and what may or may not work out cannot be predicted with certainty, despite the claims of stalwarts like Einstein and Paul Dirac that beauty and unification always reign supreme. After all, supersymmetry, despite its great allure and unifying power, is still undetected at the Large Hadron Collider. Natural phenomena may simply not care about our subjective feelings on the unifying importance of mathematical beauty!

So, is unification still germane in physics? Actually, yes. Unification is still very present, but how and where it will emerge is almost impossible to predict. The connection of quantum Hall effects to topological quantum field theories is one example. Who could have predicted that some of the most esoteric topological



Katja Dutzi, Terahertz Application Specialist

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concepts, such as modular tensor categories, manifest themselves in the current-voltage measurements of two-dimensional transistors? Yet they do in quantum Hall effects, and they continue to be relevant in the emerging subject of topological materials and phenomena now dominating condensed-matter physics.

Similarly, the Dirac equation turned out to be the right description for electrons and positrons in vacuum, but the almost equally beautiful theories of Hermann Weyl and of Ettore Majorana languished in particle physics. Whether neutrinos are Majorana fermions—that is, whether they are their own antiparticle—remains unknown. But more than 80 years after Weyl, condensed-matter researchers are discovering solid-state Weyl materials, which exhibit massless, chiral charged quasiparticles. “Chiral two-dimensional massless Dirac equation” turns out to be an excellent continuum description for graphene. And Majorana particles are central to the concepts of non-abelian anyons and topological quantum computation. (See the article by Nick Read, *PHYSICS TODAY*, July 2012, page 38, and my article with Michael Freedman and Chetan Nayak, July 2006, page 32.) Microsoft has started a worldwide effort to build a quantum computer that has non-abelian Majorana modes and topological quantum field theories at its core.

Materials physicists, many of whom never heard of Weyl and his equation until recently, are busy publishing experimental papers on the search for chiral anomalies in certain types of semimetals. That is unification at its best, but it has not followed a planned, logical course. It has happened purely through general unifying concepts that are enabling us to connect phenomena that seem completely different on first sight. Newton's spirit of unification is still alive and well, but its scale is no longer as grand as it was in 1687, because physics itself is so much grander now.

Unification still rules physics, from the graduate qualifying exam to the creation of quantum computers. We may not see it in our everyday experience of physics, but when it shows up, we immediately realize it, accept it, and use it.

Sankar Das Sarma
(dassarma@umd.edu)
*University of Maryland
College Park*

LETTERS

A memoir on project-based learning

A story in the June 2017 issue of *PHYSICS TODAY* recently caught my eye. An Issues and Events story by Toni Feder (page 28) stated that project-based learning is gaining popularity. I am a retired industrial physicist with my PhD in atomic theory. I'd like to share a related story.

I think it was my junior year, 1966–67, at Colorado State University. I was taking a course on modern physics; the class had two parts. The lecture part was traditional and worth five credits, if memory serves me, and the laboratory part would now be called project-based learning. It was worth two credits.

On the first day of lab class, the professor took us to the basement of the physics wing, unlocked the doors of three rooms, and said, “You may use any materials in this room, the next one, and the one at the end of the hall. You are to design and execute five experiments in modern physics, record the data, and make a report on each. The notebooks and reports will be turned in at the end of the quarter and will determine your grade for the class.” He then went back upstairs to his office. He was always available, but few needed to consult him.

We were teamed up into groups of two. In addition to choosing from several “canned” experiments, each group took on at least one original experiment. My partner and I chose to measure the stopping potential of the photoelectron. We found a regulated DC power supply with shielding, a student spectroscope, and a few odds and ends, and we cobbled together a credible experiment. The result was within 20% of the accepted value, a quite good result for the equipment available to us.

That class served me well throughout my career. It taught me to read what others had done, adapt their work, and solve problems with the equipment at hand, and it developed in me a passion for the projects I encountered. I had an exciting career that involved topics from repro-

gramming a direct-reading spectrograph for analytical chemistry to studying iron aluminides. The work was an equal mix of the theoretical and the experimental and was highly interdisciplinary. For example, one summer I was a student hire at Aerojet General to work on Project NERVA, an effort to develop nuclear propulsion for spacecraft.

Among other things, the project-based lab fostered a can-do attitude in me. I strongly applaud the efforts described in Feder's story.

Jack R. Woodyard
(woodyard@ruraltel.net)
Norton, Kansas

Assumptions about climate change skeptics

In his editorial in the August 2018 issue of *PHYSICS TODAY* (page 8), Charles Day writes about his interaction with a climate change skeptic. Like all of us, he has made some assumptions. The most troubling of those is that the skeptic has some understanding about the nature of science.

Day writes, “I can point out that the current mean temperature is 1 °C higher now than it was in the 1950s.” Were he to make that point and then ask the skeptic what temperature indicates, he would get some insight into how shallow the skeptic's understanding is. If he were to ask the difference between heat and temperature, Day would undoubtedly be even more dismayed.

When giving presentations to teachers and the public, I am careful to make sure the participants understand the difference between temperature and heat. I then emphasize the enormous amount of energy (heat) it takes to raise the temperature of Earth's atmosphere, oceans, and surface by just 1 °C.

I would not qualify Day's acquaintance from the embassy as a legitimate skeptic unless that person has some basic understanding of climate science.

Frank Lock
(flock@gsu.edu)
*Georgia State University PhysTec
Atlanta* 