feature article

The entangled dance of physics

Stephen G. Benka

Physics so permeates today's world that we often can't even see it.

Steve Benka is the editor-in-chief of PHYSICS TODAY.

Here are some bold statements that should surprise no one: The legacy of physics is undeniably vast, yet often goes unnoticed. The practice of physics today has a breadth, depth, and richness that is unparalleled in history, yet a great many people are blind to the very existence of physics. The essence of physics retains its elegance and profundity even as its application can render it invisible.

But wait. How can physics be invisible? Didn't physics capture the world's attention during the 2005 World Year of Physics? Aren't television programs and popular books about string theory, cosmology, and charismatic physicists gobbled up by a hungry and inquisitive public? Somewhere in the world, every day, doesn't a new physics-related story appear as a news item? Of course, of course, and of course. Despite such obvious visibility, however, I contend that physics in its broadest sense is rarely discussed and is grossly undervalued.

Nothing I say here is new, and much of it may already be obvious to you. I claim no special insight other than that of a deeply interested observer of the physics community. Still, perhaps these musings will add a little twist to your thinking; perhaps they will prod one or two of you to reconsider or refresh your own views of physics and physicists in these very messy opening years of the 21st century.

The power of "Why"

A typical scientist brings to humanity's table a confluence of special qualities. Foremost among those are three shared by most children older than a few months, that the scientist somehow hangs on to and develops into a full mindset. Those three qualities are a broad curiosity about the world and the universe; an intellectual adventurism that takes the fright out of mental risk-taking; and a deep-seated need to understand things. That last one needs elaboration because, in my view, it was a healthy obsession with understanding that drove most physicists into their studies, pursuits, and profession. Curiosity can be satisfied at many levels; adventurism can be reckless. A profound need for understanding, however, can temper and direct both of the other drives and does so for the best of scientists. Certain people find it very difficult to take someone else's word that "this is how it is because everyone says so" or "because I say so" or "because this or that authority says so." A certain type of person needs—not just thinks it would be nice, but actually needs—to find out for herself or himself why something is the way it is. And being satisfied with the robustness of the self-discovered answer, that person can continue confidently down the intellectually adventurous path of being curious about the world. Those of this ilk who go into science eventually come to appreciate the robustness of scientific results, due in no small measure to the impersonal and repeatable realities of observation and experiment. Thus, without losing an innate skepticism, scientists can come to accept others' scientific results as true and science gains a robust authority of its own.

Of course, that person with a deep-seated need for understanding could be a mechanic or a legislator, a librarian or a soccer player. Scientists have no monopoly on understanding. What sets the scientist apart is the ability to acquire and the discipline to use a specific toolkit to examine the natural, physical world in a rational, orderly way and thereby to discover something about what makes the world tick.

In the particular case of the physicist, the tools in the kit are arguably some of the most sophisticated ones available to humankind, including an impressive array of deep physical concepts and principles, a multitude of advanced mathematical and computational techniques, an ability to creatively use—and invent—relevant instruments, and a facility to reason analytically in a carefully logical progression. With such tools available, a measure of understanding of the physical world is certain. And the occasional flash of intuitive insight can be capitalized on rigorously and parlayed with some confidence into lasting results.

The physicist uses these tools in various combinations at various times to solve a multitude of problems—from mundane to esoteric, from technological to hypothetical, from essential to superfluous. With not only a healthy need to understand both the problem at hand and the possible solutions, but also an active intellectual adventurism, the physicist brings a very large toolkit to bear on that age-old question of "Why?" and its cousin "What if?" This, in my view, sums up the value of the physicist in today's world.

What is physics anyway?

But what is it that physicists actually do? What problems do they tackle? Just how do we think about this science that we call physics? Such questions are the subject of the rest of my musings here.

Readers interested in the history of physics—or of science or of natural philosophy—should turn elsewhere. Nor will I mention, except here in passing, the roots of engineering as practical applications of newly found bodies of knowledge. Instead, let's look at some snapshots of physics as we find it today.

Most current dictionaries capture physics's essence almost trivially with words along the lines of "a science that

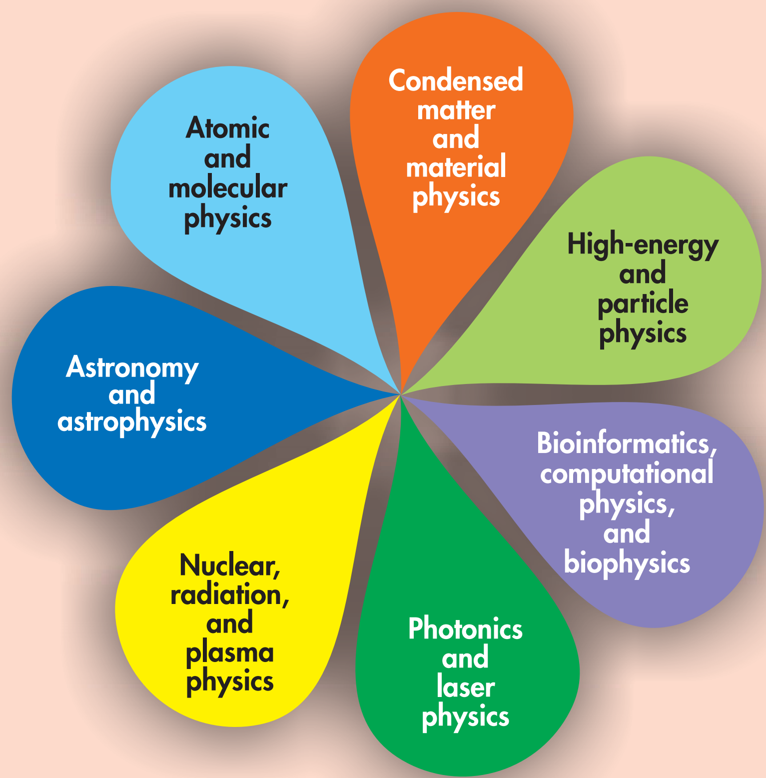

Figure 1. Physics is often seen as a collection of subfields. This particular breakdown is from the International Meeting on Frontiers of Physics, held in Kuala Lumpur, Malaysia, during the 2005 World Year of Physics. For any breakdown of physics, exciting observations and deep discoveries take place not only in each distinct area but also where areas come together. The common view of a segmented discipline, however, is in many ways oversimplified.

deals with matter and energy and their interactions." I contend that most people have no clue as to the generality inherent in that definition. Rather, they assume that if it's physics it must deal with only the most fundamental notions of matter and energy, notions connected with particle accelerators or unified forces or the origin and fate of the universe. Physics certainly encompasses those and many similarly fundamental endeavors; indeed a great many students who are drawn to physics are excited and energized by just such notions, by the opportunity to understand and maybe even contribute at the deepest level to humankind's knowledge of the universe.

But I contend that that popular perception of physics is self-limiting; as such it is misleading and does us a disservice. Thanks to the sophistication and generality of its toolkit, physics deals comfortably with energy and matter of all kinds, and all kinds of interactions between them, in all kinds of environments. Metallurgy, hearing aids, sailboat hulls, and archaeology fall as much within the purview of physicists as do galaxies, semiconductors, fiber optics, and plasma reactors.

Working physicists—those with a degree in the subject—are as likely to find their fulfillment outside of academia as in it, helping to solve very messy problems in a very messy world. Data from the American Institute of Physics show that of 4000 recent physics bachelor degree recipients in the US, only half went on to graduate school (often but not always in physics or astronomy). Of masters degree recipients, only 30% stayed in graduate school; 60% of PhDs remained in academia one year after getting their degrees.[1]

Even of those who continue to do research within academic physics, more choose to work in areas allied with today's and tomorrow's technology—areas like condensed matter physics, optics and photonics, and materials physics—than to pursue answers to eternal questions. And many working physicists have found homes in other academic departments—including the many types of engineering, as well as acoustics, materials science, Earth science, and even departments within medical schools.

Academic physics, and here I'm referring to the course work aimed at future physicists rather than at the general student population, rightly focuses on passing along the tools of physics. In fact, I suggest that a working definition of physics can be precisely that cohesive set of tools. Then the practice of physics becomes all that is or can be done with those tools.

Hints at the generality of those tools can be gleaned from the segmentation of physics into traditional subfields such as acoustics, optics, mechanics, thermodynamics, electromagnetism, atomic and nuclear physics, condensed matter physics, particle physics, and plasma physics. But I find it curious that many physics faculty members ignore the widespread applicability of their subject beyond academe, perhaps because they are not themselves aware of the extent to which physics has taken on a life of its own beyond the halls of the university.

Multiple personalities

Physics faces a serious dilemma: If it were a person, it would suffer from a severe case of multiple-personality disorder. On the one hand, it imparts an intricate array of tools and cultivates a precious mindset of rational exploration. To do that, it needs and revels in its splendid academic isolation. It is to that oasis that the top students are drawn, where they have the opportunity to learn some of nature's truths for themselves, where the thrill of seeing or discovering something for the first time will not be diminished. We can think of this academic training ground as the core of physics, where the tools are passed from one generation to the next. Life within that core can be both exhilarating and highly satisfying, even as it can challenge and at times frustrate the best of minds.

On the other hand, the unity of that core is often obscured: Academic physics is fragmented into subdisciplines that sometimes feel a need to vie among themselves for some perceived legitimacy in the landscape of physics. Some have spun off into new disciplines, even new departments. So we find dedicated courses in, for example, acoustics or fluid dynamics or heat transfer are rarely available in physics departments today; interested students must look for them elsewhere. Thus for many, physics has come to mean that particular collection of subfields allowed into the physics department and nothing else. This is a dysfunctional view of physics. Given the complexity of the modern physics curriculum, subfields are both necessary and good (see figure 1); indeed, some of the most exciting research is conducted at the intersections of two or more subfields. But isolation—whether imposed or merely perceived—of one or another subfield from others is neither necessary nor good.

On the third hand, the actual practice of physics is much broader than academic pursuits alone. This is physics in the real world. It's difficult to assess the state of non-academic physics: Do physicists there have an inferiority complex or the opposite? Have they become apathetic to or ashamed of their origins? Have they moved on to heights of discovery in new realms that academics can only dream of? The answers to such questions are hard to get, because many who live there ply their trade invisibly; we don't know how to see them.

Finally, many physicists have moved out of science and technology and have gone, with their variously sized toolkits of physics, into other human endeavors. The nature of that group is as varied as its members.

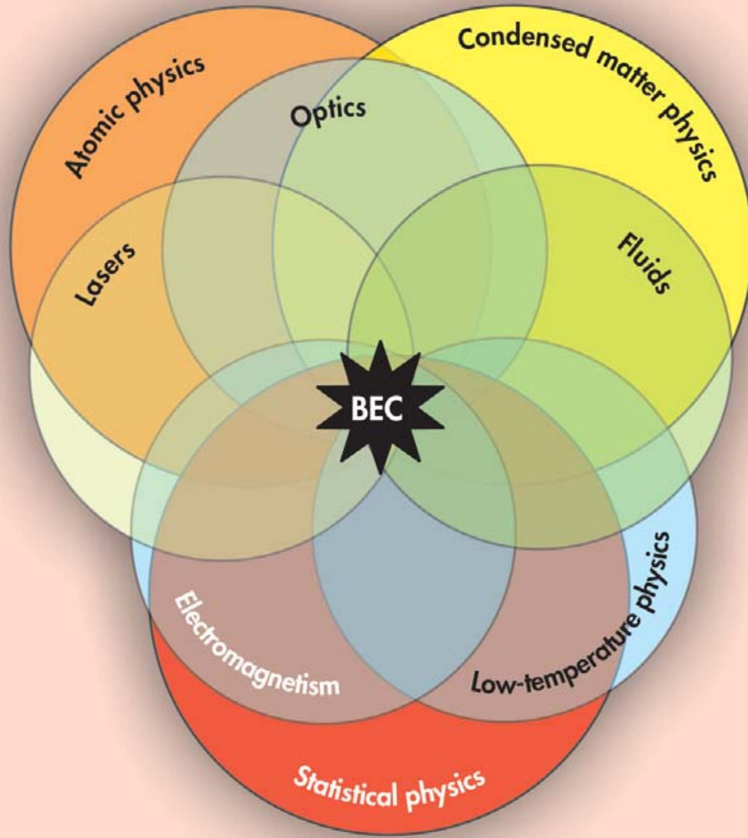

Figure 2. Bose–Einstein condensates provide an example of deep scientific entanglements. BECs exist at the confluence of several fields, and progress in each of those fields is deeply entwined with progress elsewhere. Even this diagram is highly simplified and only begins to capture the entangled nature of BEC research.

Physics entangled

Now for my entanglement metaphor, which plays obviously on quantum mechanics: An entangled pair of objects—photons, electrons, whatever—can propagate and evolve together as a unit, even while moving off in different directions, but only until one member of the entangled pair is observed. At that instant the entangled system is destroyed and a single eigenstate is detected.

The image I wish to convey is of two or more "things" with distinct identities coming together in such a way that a synergistic effect of some sort ensues, yet focusing on any one of the constituent elements destroys the synergy. The rest of my title draws a more fanciful analogy to a choreographed dance troupe or a skilled couple on the dance floor. The smooth execution of the various maneuvers presents a picture that can be marvelous to behold. As with entanglement, focusing on just one of the dancers can reveal that individual's skill and talent, but the bigger effect is lost. I don't want to push the analogy too far, just far enough for you to see where my musings are headed.

Consider the case of Bose–Einstein condensates (figure 2), existing at the intersection of atomic, condensed matter, and statistical physics, belonging to all those fields and to none of them alone. In addition, BECs could not have been produced, let alone studied, without the tools of optical physics, without manipulating electric and magnetic fields, without understanding gas and fluid dynamics, or without innovations in low-temperature physics. The experts will no doubt tell me what else I failed to mention. The point is that BEC research depends critically on the synergistic entanglement of all these sometimes separate fields of study. Take the contributions of one away and the program to make BECs collapses. It's more than interdisciplinary physics coming together to solve a problem. It's a deep entanglement of fields that gives rise to something qualitatively different, the emergence of an entirely new field.

Science splintered and sintered

There is no shortage of examples of physics entangled with itself, from soft condensed matter to plasma astrophysics. You no doubt have your own favorites. Thus, even as the core of physics might get obscured by an academic splintering into subfields, that powerful core allows physicists to continue to explore new connections and thereby sinter elements of subfields back together in new ways.

The same holds for all of science. Today, not a single branch of science remains isolated; at a minimim, the branches borrow ideas and techniques from each other. Thus, for example, knowledge of botany is needed to identify pollen found in radioactive-isotope-dated sedimentary cores drilled from the ocean's floor to study Earth's ancient climate. To be sure, each branch of science and engineering—physics, chemistry, biology, geology, hydraulics, oceanography, and the rest—has its own core from which it draws its identity and which gets imparted to students. But Science with a capital *S* is reaching adulthood as it must: Nature does not easily give up her answers to today's complex questions. That we carve her up into separate disciplines is a demonstration not of her essential nature but of our human limitations.

Such entanglements have been with us since the days of

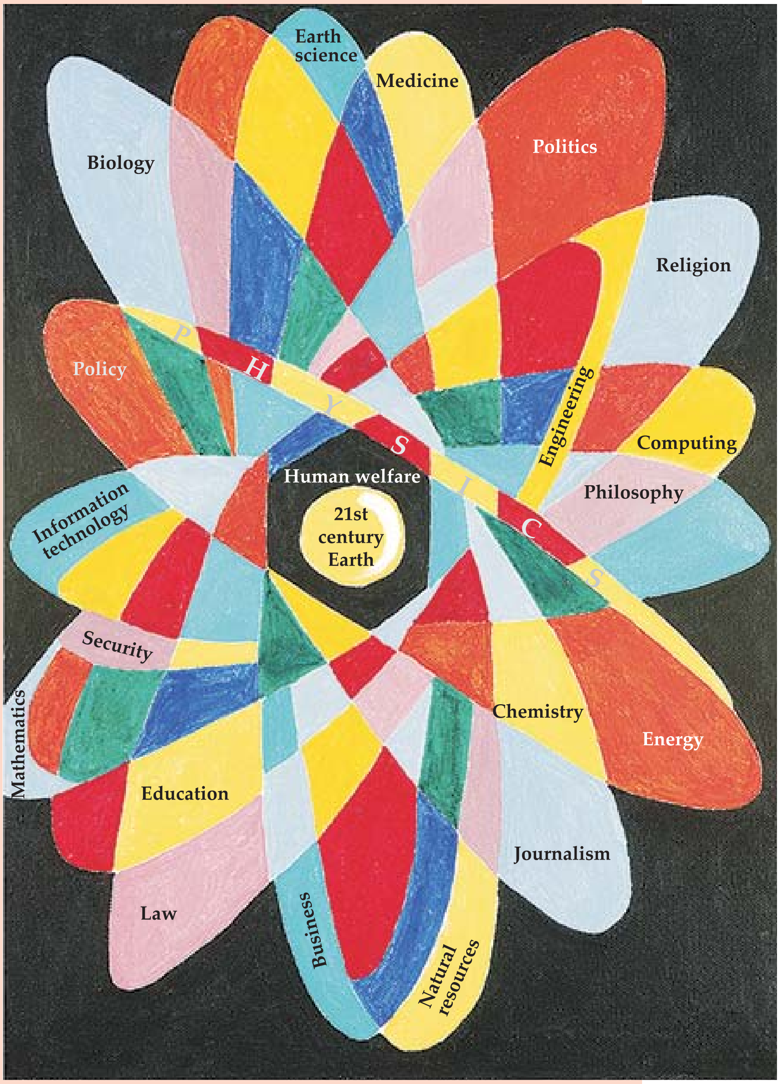

Figure 3. Our entangled world can render the general practice of physics almost invisible. Though its role is often obscured, physics remains vital to the advance of science and the betterment of humankind. (Original *Atomic Flower* painting, without labels, courtesy of Reynold Auckenthaler, www.einsteinartworks.com.)

the natural philosopher. But the current scale and number of multidisciplinary projects is unprecedented.

Since the 2001 federal budget, the poster child for multidisciplinary efforts in the US has been the National Nanotechnology Initiative. With research funding in 13 federal agencies, the NNI "plays a key role in fostering cross-disciplinary networks and partnerships."[2] In November 2006 the NNI website offered the following as some recent achievements in nanotechnology:

▶ Use of the bright fluorescence of semiconductor nanocrystals (quantum dots) for dynamic angiography in capillaries hundreds of micrometers below the skin of living mice—about twice the depth of conventional angiographic materials and obtained with one-fifth the irradiation power.

▶ Nanoelectromechanical sensors that can detect and identify a single molecule of a chemical warfare agent; an essential step toward realizing practical field sensors.

▶ Nanocomposite energetic materials for propellants and explosives that have more than twice the energy output of typical high explosives.

▶ Prototype data-storage devices based on molecular electronics, with data densities more than 100 times those of today's highest-density commercial devices.

▶ Field demonstration that iron nanoparticles can remove up to 96% of a major contaminant (trichloroethylene) from groundwater at an industrial site.

The NNI is just one multidisciplinary research effort in the US. The NSF currently has 53 active "crosscutting and NSF-wide" funding opportunities. A typical example is the Materials Research Science and Engineering Centers program. The first MRSECs were established at 11 universities in 1994; today there are 29. According to the NSF, each MRSEC is to "undertake materials research of a scope and complexity that would not be feasible under traditional funding of individual research projects" and must take "an interactive, interdisciplinary approach to materials research."[3] Even a small MRSEC can have nearly a dozen participating faculty members representing four or more departments.

Multidisciplinary programs are now commonplace, necessitated by the complexity of the problems tackled and the recognition that no single discipline, no matter how rapidly advancing or sophisticated, is adequate to the task. The problems cover aspects of vital issues of the day like energy supply and delivery, climate and environmental change, and technological innovation. What's more, the programs of individual nations are often entangled with each other in our globalized world. One of the earliest may have been CERN, the European particle-physics center. (See *I. I. Rabi and the Birth of CERN*, by John Krige, PHYSICS TODAY, September 2004, page 44.)

Within any one of those multidisciplinary and globalized efforts, physics may or may not play an explicit role. When it does, it is but one entangled element that calls for certain personality traits in the physicists involved: Give and take is essential to work effectively with others, and humility is needed to learn from them. Even when not explicitly identified, physics is never far from any scientific endeavor. One is hard pressed to find a multidisciplinary effort that makes no use of the tools and instruments of physics, even if the roots of those tools and instruments are lost to the participants.

Impressive as the government-funded programs are, in a sense they just mimic what the private sector has done for well over a century—entangle people and tools and ideas from different backgrounds to synergistically create innovative new products and drive economic growth.

Dancing with the world

I recently went to a conference attended by users of a particular commercial software package developed to model physical systems. The software allowed users to exploit various pieces of physical science—electromagnetics, acoustics, structural mechanics, chemical reactions, properties of materials, and others—either separately or in concert. The very existence of such a package is testimony to the entanglement of science needed to address real-world problems.

On one side of me at dinner sat a fellow whose job is to optimize the use of equipment and machinery for the manufacture of polymer-based diapers; he works to achieve high throughput without tearing, melting, or otherwise damaging the product, while minimizing waste. His employer is a large corporation well known to American householders; his background is physics. Sitting on my other side was the director of research and development for a company in upstate New York that makes electromagnetic sensors of all kinds. One of his favorites measures the dielectric properties of asphalt to determine when it is optimally compressed to make the best possible road surface. His background, too, is physics.

Curiously, the two physicists see themselves as engineers. The software company sees everyone as engineers. Its product incorporates sophisticated algorithms to solve a dizzying variety of physics-related partial differential equations and even has "physics" in its name. Yet the physics and the physicists with whom the software company deals are so thoroughly entangled, both with the set of problems to be solved and with the companies and other entities working on solutions, that they have become invisible. The pervasiveness of physics, indeed its very existence, is not always apparent even to those who work with it every day (figure 3).

Here is an observation that I find as relevant today as it was when made 50 years ago by Mervin Kelly, then the president of the Bell Telephone Laboratories: "The ivory-towered existence is no more and, like it or not, the physicist is in the midst of the fast moving currents of the day in our society." (See Kelly's article in PHYSICS TODAY, April 1957, page 26, available online to subscribers.)

Many physicists no longer do science at all. Enriched with their toolkit, they've moved on to other fields, perhaps law or public service, or maybe they've become business entrepreneurs or consultants. Or any of a hundred other possibilities. They might philosophize about religion, truth, and different ways of knowing. Some even become editors. Those pursuits, as with physics itself, are not undertaken in isolation but rather are the product of the practitioner's training and mindset and of the state of the world as seen at the time. Even if the world-entangled physicists eventually lose their identity with physics and swell the ranks of the invisible, nevertheless they remain physicists by temperament and training, bringing a much-needed rationality to non-science-related matters that far too often devolve into seemingly irrational behaviors.

Does it matter that a large subculture of physics is invisible? It depends on who asks the question, on who wants the answer. Those concerned with the essential and exhilarating work of advancing the core of physics must answer, "Yes, it matters greatly." For them, the value of physics is in physics itself; its visibility can never be high enough to attract all the bright students that could contribute. But for those who are more entangled in broader pursuits, the answer is "Not necessarily." For them, the value of physics is in what it brings to the table; the end result is what matters. That physics might not get due credit for the part it plays is immaterial to the success of an invisible physicist. In any case, those driven to acquire the tools of physics, driven by curiosity, intellectual adventurism, and a compelling need to understand, will continue to make lasting contributions.

References

1. See http://www.aip.org/statistics/trends/phystrends.htm for the various "One Year Later" trend reports.
2. See the website for the National Nanotechnology Initiative at http://www.nano.gov/html/about/home_about.html.
3. See NSF's MRSEC website at http://www.mrsec.org/home/about.php3. ■