A century of physics: 1950 to 2050

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Physics had quite a century: quantum mechanics, nuclear power and weapons, giant particle accelerators, the transistor and the myriad of quantum devices that followed, and a host of remarkable discoveries from quarks to dark energy. Any doubt that physics was king in the 20th century was dispelled when *Time* magazine named Albert Einstein as its Person of the Century. Moreover, the US was arguably the mecca for physics from 1950 to 2000, with the most Nobel Prizes, the biggest accelerators, and the leading journals.

The world has changed profoundly over the past decade. Biology has emerged as the marquee science of the 21st century. From genome sequencing to functional magnetic resonance imaging, the breakthroughs in the biological and life sciences—many enabled by instrumentation from physics—have indeed been stunning, and more lie ahead. Moreover, the US will not dominate physics—or the world economy—the way it has for the past 50 years. All this has nervous physicists in the US (and elsewhere) wondering whither physics in the 21st century.

I don't think science per se is—or should be—the focus of our nervousness. Our legacy provides a firm foundation, and the opportunities ahead are breathtaking. Rather, I think we are skittish because of the change at hand and the uncertainty ahead: It was good to be king, and it's hard to step down from the throne.

Motivated by the angst I perceive, I will take stock by discussing a century of physics, roughly centered on the present. That time frame allows me to reflect on past accomplishments and discuss future opportunities, finishing with my thoughts on how the nature of physics is changing and where physics should be heading.

Greatest hits: 1950–2000

With so many important advances, it is hard to identify the highlights of this exciting period. So I will focus on the advances that changed the game and moved physics into new directions, though I recognize that such a list may reveal as much about the chronicler—a particle theorist turned astrophysicist and cosmologist—as about physics itself.

Quarks. The discovery that the building blocks of nucleons and the other strongly interacting particles are six fractionally charged quarks has had profound consequences across physics. It led to the standard model of particle physics, changed the discussion about the inner workings of nuclear matter, opened the door to the study of the quark–hadron transition in heavy-ion collisions, and allowed fruitful speculation about the universe less than a microsecond after the Big Bang.

Neutrinos. Postulated in 1930 by Wolfgang Pauli to save the principle of energy conservation, the feebly interacting neutrino eluded experimenters for another 26 years. Neutrinos are now understood to be the uncharged partners of the electron, muon, and tau leptons; collectively, quarks and leptons are the building blocks of matter. Although neutrinos are the lightest and most inert of nature's building blocks, they are a critical component of the explosions of massive stars that produce heavy elements, contribute about as much mass to the universe as do stars, and are probably critical to the very existence of atoms by helping to create the asymmetry between quarks and antiquarks.

The triumph of field theory. The once purely formal topic of field theory—referred to by some as math, not physics—delivered on its great promise. Not only has it provided the $SU(3) \times SU(2) \times U(1)$ gauge theory of the standard model of particle physics and a framework for unifying all of the basic forces, but it also led to the standard theory of superconductivity and to the renormalization group and conformal field theories that describe a host of condensed-matter systems. And let's include general relativity too, which finally transitioned from poorly understood mathematics to an essential tool for understanding the evolution of the universe and many of the most interesting objects in it.

An extreme universe. In 1966, the mysterious quasars burst on the scene; they are now known to be powered by the supermassive black holes that inhabit the centers of galaxies. Subsequent discoveries of stellar-sized black holes, neutron stars, and cosmic rays with energies up to 10^{20} eV revealed that the universe is not the peaceful place we once thought it to be, but rather a far more interesting place of extreme energies, densities, and gravitational fields. Those discoveries not only brought more physics into astrophysics but also turned the heavens into a physics lab.

Cosmology and cosmic convergence. The discovery of the cosmic microwave background, an ensuing flood of data, and powerful ideas arising from the convergence of the very large universe with the very small entities of particle theory have combined to effectively turn cosmology from a backwater activity frowned on by physicists to one of the hottest tickets in all of science (see PHYSICS TODAY, December 2008, page 8). Deep connections are now being revealed—in dark matter and dark energy, inflation, neutron stars, and neutrinos—between the outer space of the cosmos and the inner space of elementary particles and nuclei.

Quantum mechanics at work. Physicists harnessed the quantum mechanical world of atoms and produced practical devices—including transistors, integrated circuits, lasers, and superconducting wire—that transformed the way we live and made possible the information age, arguably the most stunning example of the tremendous payoff of curiosity-driven basic research.

Computational physics. Moore's law marched through 12 orders of magnitude over the past 50 years, from kilobytes and kiloflops to petabytes and petaflops, and made possible a new branch of science—numerical simulations and experiments. Theories as complicated as quantum chromodynamics and general relativity can now be attacked numerically; the properties of elementary particles can be computed from first principles, black hole collisions can be envisioned, and even the universe can be simulated.

New eyes and new instruments. Instrumentation created by physicists has impacted all of science. Accelerators provide not only eyes on the world of quarks and leptons but also intense x-ray beams to image and study biological and material samples. Detectors for microwave, IR, UV, x-ray, and gamma-ray photons—and soon gravitational waves—have given astronomers new eyes on the universe. Individual atoms are routinely trapped, manipulated, and studied, and the atomic world is imaged by multiple techniques.

Opportunities: 2000–2050

The game-changing advances of the past 50 years provide clues about the questions that are ripe to be answered and the most promising physics to pursue. The past will be a hard act to follow, but I think the next 50 years may produce an even more impressive record of accomplishments and discoveries. Here's what I foresee:

At work in the world of atoms. We can image atoms and have begun to manipulate them. The next challenge is to do real work at the atomic level: Create new materials and small machines, construct hybrid physical–biological materials, and more generally realize the great potential of the nanoworld. The societal impact could rival even that of quantum mechanics.

Marriage of quantum theory and gravity. Those two theoretical pillars of 20th-century physics are incompatible. String theory aspires to bring them together and may or may not succeed, but the reconciliation is ripe to be realized. When it is, our understanding of the nature of matter, energy, space, and time and of the origin and evolution of the universe will deepen. And who knows, there might eventually be practical spinoffs, just as there were for quantum mechanics.

The complete story of the universe. Cosmologists are poised to put the universe's timeline together, from before the Big Bang through galaxies, stars, planets, and life, to the end of time. With bold ideas and the powerful Earth- and space-based telescopes planned for the next decades, we are likely to be immersed in a golden age of cosmology.

Sustainable power. The world needs to go from 10 terawatts of total energy consumption to 40 TW in 40 years or so, in a sustainable way and with minimal impact on our planet. Although there is a wonderful array of possibilities, from solar to nuclear and from biofuels to carbon-sequestered fossil fuels, the complete solution is not yet on the shelf. Physicists will be key participants in the basic research needed to solve this grand challenge for humankind. If we succeed, the achievement is likely to be better remembered than nuclear weapons.

The physics of living things. With the ability to physically measure and operate on atoms, molecules, and cells, we may be close to answering some big questions: How does the brain operate?

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What is the information in the genome? How do biological machines work, and can they be imitated or even reprogrammed? New tools will be crucial, but so will big ideas and organizing principles for understanding and describing the complex systems of life.

Are we alone? With more than 350 planets now known to orbit nearby stars and with several plausible locations for life forms within our own solar system, finding life beyond Earth seems like a sure bet. Actually doing so would have profound implications for biology and astronomy and for how humanity views itself. Now imagine that we find intelligent life.

Complexity and emergence. I have always liked the metaphor of a child watching chess to convey the mission of physics—namely, that we carefully observe Nature to discover her underlying rules. Of course, knowing the rules doesn't mean you understand the game. That is especially true in complex systems, whether turbulent fluids or living organisms. Understanding complexity and the emergence of large-scale behavior remains a big challenge.

Instrumentation for the 21st century. No one does it better than physicists when it comes to innovation in instrumentation, and thus the future of all scientific fields surely rests in our hands.

Whither physics?

One might think that with a striking record of accomplishments and the tremendous opportunities ahead, physicists would be as confident as ever. Instead, there is self-doubt. The rise of the life and biological sciences has leveled the playing field: No longer do physicists occupy the lion's share of leadership positions in academe and science; no longer do all the best and brightest students aspire to be physicists. Within science there is fierce competition for resources, for the next generation of scientists, and for glory. Add to this the fact that in the larger context, science is undergoing dramatic change: It is more collaborative, more interdisciplinary, more international, more digital, more expensive, and more fast-paced.

To flourish, physicists must have the confidence to reinvent physics, as we have in the past. With many of the most exciting opportunities at the boundaries with other disciplines, physics must skillfully accommodate a greater variety of activities. It is easy to imagine a balkanization, with departments of astrophysics, biophysics, computational physics, materials physics, applied physics, and so on, but no physics department per se. That is the route biology—and even chemistry—has gone, but I don't think disciplinary fragmentation would best serve physics.

There is an important unity in how physicists approach problems. Physicists use rigorous and quantitative methods; they search for underlying principles and fundamental laws; they begin with simple models and add complexity; and they rely on reductionism and innovative instrumentation. While the name of the activity remains the same, the foci change—so much so that the only robust definition is that physics is what physicists do. Physics has evolved from earthly and celestial mechanics 400 years ago to include electricity, magnetism, and statistical mechanics in the 18th and 19th centuries; and today it encompasses materials, atoms, nuclei, elementary particles, the cosmos, and a growing number of aspects of biology. Its practitioners have invented new tools—mathematical, conceptual, and instrumental—to get at the most urgent questions of their day. In the very best sense, physicists have been and will continue to be scientific opportunists. Another Chicago physicist before me, Albert Michelson, is infamous for having declared physics dead a century ago. I will not repeat his mistake: I am bullish on the future. You'd have to be crazy to bet against physics. ■