PHYSICS AND DEVELOPMENT

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Summary

This paper reviews milestones of twentieth-century physics and proceeds to an analysis of applications of physics to society. Finally, a brief review is given of the legacy of twentieth-century physics for scientists of the twenty-first century with the customary exuberance of the physicist, but with a cautionary note on the essential need for a far higher level of public understanding of science than now exists.

1. Introduction

This perspective on milestones in physical sciences is constructed so as to put equal emphasis on basic research and on applications of fundamental knowledge. Applications influence the world in two ways:

1. They increase the capability to advance our knowledge base; and
2. They create wealth and capability for affecting life support systems and sustainable development.

The fact that basic research, even the most abstract and fundamental, can provide seeds of our technological civilization, is not appreciated by the general public or even by the political process that funds the research.

2. Milestones of Physics

Physicists like to describe their domain as the science of the most fundamental aspects of nature. If you challenge this most physicists will remind you that the realms of physics extend from the sub-nuclear world of fundamental particles to the whole of the cosmos—time spans are relevant from a billionth of a trillionth of a second to the age of the universe. But before physicists go too far, disturbing questions may bring pause. Mere philosophy perhaps, but there are questions most physicists dismiss today as outside of physics. These include: “Why does the universe exist?” “Why is there something rather than nothing?” and “Why is mathematics, a creation of human thought, so unreasonably relevant to nature?” I throw a piece of chalk across the lecture room and it describes a parabola. The trajectory of the Earth around the sun describes an ellipse. Why does nature conform to mathematics, a pure invention of the human mind?

Nevertheless, physics has molded the shape of modern society. The belief that there is order in the natural world and that the human mind can understand that order was handed down to us by the ancient Greeks, widely acknowledged by historians of this epoch to be the first scientists. Since then, physicists have devised experimental tools to observe and measure and we have devised theories that allow us to comprehend what has been observed and measured.

In the process of understanding the world, physics has generated new technologies, which have changed the way people live, and these technologies have also empowered physics and its neighboring sciences to further advances.

The history of physics is not simply a history of major triumphs following in relentless order. It is a complex weave of ideas building on ideas, of wrong turns and dead ends. Theoretical physicists have a hard time. As Einstein noted, a theory can never be proved—only disproved. The best the laboratory result can say about a theory is: “maybe?” But it more often says “No!” The hardest blow, but perhaps the most interesting, is when the “No!” comes after a series of brilliant “maybe’s”. But we do have milestones, perhaps six major revolutions, and substantial additional advances.

2.1 Major Revolutions

1. In 1687, Isaac Newton published *Principia Mathematica*, a summary of his contributions to physics. Its impact rivals any single body of work in the history of

mankind. From it flowed a succession of profound changes in human thought and capabilities.

Newton created mechanical engineering. Bridges, tunnels, skyscrapers, cars, ships, planes—all are designed on Newtonian principles. His syntheses led to an understanding of the motion of moons about planets, and planets about the Sun. Today, his equations are programmed into NASA's computers to control the motion of space vehicles.

But his deepest impact was the recognition of how orderly the world was and that this order could be understood and used.

2. A comparable revolution, led by Michael Faraday and James Clerk Maxwell, took place in the nineteenth century. The nature and behavior of things electrical—currents and charges, magnetism and the electrical nature of light—were unified into one comprehensive theory. That so huge a variety of phenomena could be described by a few beautiful equations furthered the idea that the world was indeed knowable. Experiments by Cavendish and Coulomb, and by Ampère and Faraday, laid the foundation of Maxwell's electromagnetic theory.

3. In 1824 Sadi Carnot, a French Engineer, examined the workings of an "ideal" engine, adopting the process of carrying the engine through a complete cycle so that the working substance is brought back to its initial state. His results were put in modern form by Clausius and Lord Kelvin.

   Today it is learned as the Second Law of Thermodynamics, which states that engines that are driven by input heat energy, in order to perform work, must exhaust thermal energy into an environment which is at a lower temperature than the input heat source. This presents a depressing limit on the efficiency of engines. An equivalent statement is that heat cannot spontaneously flow from a lower temperature source to a higher temperature source. Incidentally, the First Law of Thermodynamics is a restatement of the Law of Conservation of Energy.

   The implication of the second law is that you cannot turn thermal energy, e.g. the heat content of the ocean, into work (i.e. useful work) without having a colder place into which to discharge heat energy. Heat driven engines must operate between two systems with different temperatures. This places a serious limit on the efficiency of heat engines—even perfect engines—with no friction. In the industrial revolution that turned on in the late nineteenth century, the Second Law was a guiding influence. The implications for the future of the universe are equally sobering.

4. The beginning of the twentieth century was distinguished by a remarkable decade ending in 1900. During this period, X-rays were discovered (Rontgen), radioactivity was discovered by Bequerel, the electron was discovered by J. J. Thomson, and in 1890 Max Planck made the first attack on the mysteries of atomic structure by proposing the existence of quanta. It was as if nature revealed a host of its deepest secrets to celebrate the start of a new century, the last of that millennium.

Knowing the existence of the electron as the carrier of electric charge was the key discovery leading to the solution of a problem posed by the Greek philosopher, Democritus, in 450 BC—the atom.

5. The conquest of the atom led by Ernest Rutherford, Niels Bohr, and others between 1910 and 1930 gave rise to quantum mechanics, which revolutionized physics, most of chemistry and an important part of biology. Quantum theory gave us a unified and comprehensive command of the atomic world. The creation of quantum mechanics came from observations of how heated matter glows red, then white. Phenomena at the level of the atom could not be understood using the physics of Newton and Maxwell. A radical break was devised. This provided an extraordinary new framework for portraying physical reality, revolutionizing our most fundamental concepts of measurement. Counterintuitive, conceptually disturbing, but it worked. The understanding and control of atoms, molecules and solids is basic to chemistry, biology and many other sciences. In every application, to atoms, nuclei and sub-nuclear particles, quantum mechanics gave us new understandings. And it was profitable! New industries such as semiconductors, optical communications, and microelectronics continue to create new technologies, and new materials and devices like the ubiquitous laser.

   The discovery in 1947 of the transistor effect paved the way for the computer revolution that has changed everything from the way business and governments are managed to the day-to-day operation of our households. The subsequent telecommunications revolution impacts politics and knowledge acquisition and dissemination. The pace at which it is changing our lives shows no sign of slowing.

6. In 1944, one of the creators of Quantum Mechanics, Erwin Schrödinger, wrote a book entitled *What Is Life*? It is difficult to exaggerate the importance of this work because it was the “naïve physicist’s” surmise that the genetic code is inscribed in the quantum mechanical structure of complex protein molecules. Schrodinger’s book represents a bold attempt to understand the deepest mysteries of living things. Its influence on James Watson and Frances Crick had much to do with their decision to study the structure and function of DNA. The rest is history, as this 1950s discovery created modern, molecular based biology. The technological consequences of the biological revolution follow close behind and are having a tremendous influence on man’s control of disease, the structure of viruses, the applications of useful bacteria, agriculture, the ability to design drugs, and many more applications.

7. Einstein gave us a new view of the cosmos and a new and unified view of the nature of space and time. Special and General Relativity took their place alongside Quantum Mechanics as the great intellectual revolutions of the twentieth century. Whereas vast new powers were made available to humans, we were made aware of our perilous perch on a tiny planet, a mere foundling in the cosmos of billions of suns expanding from a primordial explosion. The mind could now reach to the edges of the universe. Cosmology and early universe astrophysics would lead us to a new story of creation and evolution of the universe, from its fiery origin in a Big Bang to

the 1990s discovery that the pace of the universe’s expansion is increasing. All of this was supervised by Einstein’s equations and insights.

His special theory of dealing with the abstract consequences of space, time, energy and motion had profound applications and we explore some of these now.

2.2 Additional Milestones in Physics

Nuclear Physics: In the 1930s came the assault on the nucleus, occupying only a millionth of a billionth of the volume of the atom. Larger scientific tools were needed. The nucleus became familiar territory: nuclear energy, nuclear medicine and horrendous weapons. Nuclear magnetic resonance imaging and CAT scans revolutionized medical diagnostics. Radioactivity was understood for its power and its peril. And the nucleus of the atom is a collection of nucleons, protons and neutrons, densely packed.

(a) *Particle physics*: Each nucleon is a bag of confined components: quarks and gluons. The experimental efforts of nuclear physicists towards the end of this century are to exhibit the change of state from rigorously confined quarks to a plasma of quarks and gluons.

Thanks to particle accelerators, the 1960s witnessed the beginnings of a new organization of the stuff from which everything is made: us, our planet, and the sun—the whole works! Even the creation and evolution of the universe were beholden to this synthesis of particle and force. The summary made in the 1980s is a concise table of the particles called: The Standard Model. Quarks, leptons and force-carrying particles are arranged in a concise summary of everything that has been learned since the discovery of the electron in 1897. This summary cried out for new observations that would account for particle and force complexity.

(b) *Condensed matter physics*: This deals with advances in our understanding of semiconductors, superconductors and new states of matter, such as the super-fluid phase of liquid helium 3. Areas of great activity include studies of phenomena at surfaces, the role of interfaces between different materials, disordered systems, surprising new forms of ordered systems, onset of turbulence and the new high temperature superconductors.

(c) *Lasers*: Intense beams of cooperating photons are used in surgery and supermarkets and they have also revolutionized the study of atoms, molecules and optical systems. The behavior of single, isolated atoms can be studied. Chemical reactions can be watched as they take place. New and ultra-precise atomic clocks have been used to test the tiniest effects of general relativity to high precision.

(d) *Plasmas*: Most of the visible matter in the Universe is composed of plasmas—that form of matter in which neutral gases are composed of positive ions and unbounded electrons. We need to understand plasmas to understand stars, stellar winds, planetary magnetospheres and galaxies. On earth, high temperature plasmas are grist for a future supply of energy via controlled fusion.

3. Overview of Applications

3.1 Introduction

The case for very basic research (VBR), that is, research driven by curiosity, in advancing energy-related science and technology, as well as advancing the overall scientific and technological enterprise, traditionally rests on history. In Newton’s time, the elementary objects were falling apples and orbiting moons. The unification of these phenomena was the first in a series of syntheses, which today promises to furnish us with a complete understanding of the strong, weak and electromagnetic forces. In between, VBR claims the adherence of those scientists who reduced heat and thermodynamics to mechanics e.g. Bernoulli, Joule, Kelvin, Clausius, Boltzmann and Maxwell; those who established the laws of electricity, magnetism and physical optics such as Coulomb, Cavendish, Oersted, Ampere, Faraday, Maxwell and Hertz. The atomic age was ushered in by Lenard, Rontgen, Lorentz, Thomson, Rutherford, Bohr, and Einstein. Nuclear physics began with Bequerel, Curie, Joliot, Rutherford, Chadwick and Lawrence among others. The quantum era found VBR adherents including Schrodinger, Heisenberg, Born, Pauli and Dirac preparing the way for the modern quantum field theorists like Fermi, Lamb, Schwinger, Feynman, Tomonaga and Gell-Mann. This is a very incomplete listing of the intellectual heroes who have given us our heritage.

It is hardly controversial to claim that the scientific underpinning of all of modern science and technology rests on the achievements of basic research up through the 1950s. It may not even require the credentials of historical scholarship to establish that each major synthesis from Newton to Feynman has had a profound effect on the state of science and technology as it exists today.

Before proceeding further, one should acknowledge the complete synergy of basic research and technology. It is accepted as totally obvious that basic research, rests heavily on the available technology. It is for this reason that progress in science and technology is highly non-linear, the slope of progress, continually increasing with time. It is in fact the dependency of modern basic research on a large and costly technological support that creates the current need for wise science policy. VBR is in general expensive and is absolutely dependent on national science policy. There is also a symmetrical dependency—national policy must recognize the increasing need for new understandings to cope with technologically-driven societal crises of which energy sufficiency is only one in current fashion.

It is easy to make a long list of crises and potential ecological disasters: threat of nuclear war, global climate change, ozone layer depletion, acid rain, global oil spills, nuclear reactor accidents, shortages of minerals, increasing vulnerability to terrorism, food shortages, explosive costs of health care, etc. We recognize that all of these are generated by existing technology. The virtues of VBR are increasingly suspect in view of these possible calamities. However, the debate is sophistry. It is too late. Science has delivered an enormous amount on its promise of the good life but both in distribution and in ever increasing possibilities for fulfillment, there is much to do, including the thwarting of potential and real disasters. That these can be managed is the hope engendered by the rational view, which must, in this context, be shared by all of society. If we fail, the survivors, if any, may well envy the life of the fifteenth-century peasant.

Society has long since passed the point of no return and must be fully committed to a faith—a belief in the ultimate benefits of rationality. We are not really debating the principle of societal support of basic research; we are haggling over the price.

It is in this historical context that the relevance of VBR to the health of science, technology and the general welfare, including energy-related capability, in the coming years can be discussed. This is possible under three headings: Culture, Direct Effects, and Indirect Effects.

There is continuity in the way each of these activities returns benefits to society. Culture, the most important impact, takes the longest and most circuitous route. It is therefore the least obvious. Direct and indirect effects of VBR take increasingly shorter and more obvious routes. The conclusion stresses the need for a thorough study of some of the issues that require sharpening, if these considerations are to offer any guide for policy.

3.2 Cultural Matters

Many colleagues are astonishingly shy about raising the cultural issue in full view of policy makers. Part of the reason is that the issues are philosophical and hence cannot possibly hold attention or compete in times of sociopolitical-economic crisis. It is difficult to establish that fraction of the GNP, which can be identified with the cultural value of science. It may also be true that many scientists who should know better tend to forget how they got here and it may well be that policy makers are to be credited with a much greater sensitivity and appreciation of this issue. In this regard I recommend reading the Hearings before the Joint Committee on Atomic Energy, especially in the years 1965–1973.

It is a general conviction, that this most important issue cannot be overemphasized. Basic scientific research is not only for development and the advance of life support systems. It is primarily for culture. It is for continuing to refine our scientific worldview. For this it deserves the support of society. Society must care about science in the same way that it must care about its other creative intellectual activities such as art, music and literature. The close analogy of the intellectual processes in science and art has been drawn in many places. Richard Feynman, in one of his "'Lectures on Physics," defends science as an aesthetic activity: "Poets say science takes away from the beauty of the stars—mere globs of gas atoms. I too can see the stars on a desert night, and feel them. But do I see less or more?"

The point he and many others make is that rational thinking, by recognizing causes, relationships and mechanisms, adds to the perception of beauty and richness of natural phenomena. "It enhances and humanizes our appreciation of nature."

There is, however, the valuable distinction that art, music and literature have a significant base of support from the public and from private philanthropy. We must acknowledge that society may not yet be ready to allocate to each of its cultural activities the required resources. In the interim, adherents of VBR science, bend to other arguments, which we will detail below. However, even if we make the assumption that high energy physics and extra-galactic astronomy will never have any direct utilitarian applications, we will insist that they effectively influence the advance of useful science in at least two ways. One has to do with recruiting. The other has to do with setting standards of rigor and quality, and with maintaining the esprit of the scientific community.

As already stated, studying apparently remote and exotic regions of inner and outer space is an example of the kind of rational behavior our society is committed to—we want to do as well as we reasonably can in these matters. It reinforces our behavioral style; it is part of our faith that it is good to know these things. And we keep discovering surprising connections—organic molecules in space and clouds of neutrinos that may weigh something. These remind us of the unity of science and are therefore applicable at home.

If the cultural value of these sciences is not given its required weight in long-range science policy planning, we will have a second-rate enterprise—innovation and progress will slow and the carefully debated issues of “How much solar?”, “What pace fusion?”, and “More into surface physics” will not, in the long run, amount to very much. To appreciate the power of the cultural drive, one must spend enough years with undergraduates or, even more dramatically, with high school students such as those who enter science fairs and watch Star Trek. It is out of these culturally agitated young people that the genius will come to solve our many problems in unexpected ways. No long-range strategy devised in Government conference rooms will work without the flux of new entrants into the field and without the intellectual heroes that draw them.

The earliest drive towards explanations of how things work was a cultural one. And it is the cultural appeal that has attracted the best minds into science. Whereas the guarantee of an economic and clean source of energy may be the most crucial scientific problem of our day, the bright high school student will more often be drawn to science by the puzzle of neutrino mass, antimatter and the big bang theory of creation. Not only is pure science a recruiting factor but its success sets standards and reaffirms confidence among workers throughout the spectrum of science. Victor Weisskopf calls this the intrinsic value of science:

> Basic science is a most powerful element in the philosophy of our time … and leads to a more intimate relation between man and the things in nature. It creates an awareness ... of connections between phenomena … how everything depends on everything—of how the universe, the atom, and the phenomena of life are one and co-exist.

Weisskopf goes on to speak of the community of scientists formed by the culture of the subject:

> The most rewarding moments in the life of a scientist are certainly those when he himself has found something new. But there are also those moments when he is about to realize some new essential insight made by others, by reading a paper or by listening to a presentation. There is this peculiar joy of insight, of recognizing some deeper coherence in the fabric of nature. These moments of recognition may be rare but they are an essential element in forming the scientific community.

An interesting anecdotal illustration of the cultural drive involves that quintessential technological breakthrough of modern times—the transistor. In this example, an element in the motivation was the importance of finding active solid-state circuit elements. This 1947 discovery owed much to parallel technological developments but fundamental to the discovery was the prior application of the quantum mechanical explanation of the band structure in semiconductors in 1931 by A. H. Wilson. In *Adventures in Experimental Physics* (1975) Walter Brattain wrote:

> The transistor came about because fundamental knowledge had developed to a stage where human minds could understand phenomena that had been observed for a long time. In the case of a device with such important consequences to technology, it is noteworthy that a breakthrough came from work dedicated to the understanding of fundamental physical phenomena, rather than the cut-and-try method of producing a useful device.

The effort to convey the importance of the cultural content of scientific research to policy and budget makers deserves serious scholarship. There is much to explore. Sensitivity to the cultural value of science leads to considerations of other aspects of culture in society and to a more harmonious coexistence of science in society.

The late Soviet physicist Artem Alikhanian told this story: During the siege of Leningrad in the Second World War, he and some colleagues were excused from full time defense work in order to work on the design of a synchrocyclotron—the accelerator which was eventually constructed in Dubna in 1955.

Now a siege is clearly a socioeconomic crisis of major proportions and Alikhanian's story can be interpreted as evidence that someone in authority assumed they would overcome the crisis and that a high-energy accelerator would be important for society in the future. It may be that the Soviet authority was far-sighted enough to foresee a utilitarian role for what seemed to the physicists like a purely cultural activity.

Science, the cultural part, has a deep influence on general philosophy—on the way humans think of themselves and their place in the world. The "spaceship Earth" concept of a new humility and of even newer environmental concerns could hardly have been invented before Copernicus. And, in spite of discouraging setbacks e.g. Creationism and Laetrile, vast progress has been made in general scientific enlightenment. Keith Thomas, in writing about the repeal of Witchcraft Laws in England in 1736, concludes:

> The absurdity of witchcraft could henceforth be justified by reference to the achievements of the Royal Society and the new (Newtonian) Philosophy.

He also quotes Richard Bentley:

> What then has lessened in England your stories of sorceries? Not the growing sect of free thinkers but the growth of Philosophy and Medicine. No thanks to Atheists but to the Boyles and Newtons.

Science makes its own contribution to general culture along with art, literature, music and the social sciences. In this sense, it creates a society whose well-being and energy sufficiency are worth preserving, to paraphrase R. R. Wilson:

> In a Congressional hearing on the Fermilab budget, Wilson was asked if the accelerator would help national defense. His now classic rejoinder was: “No sir, but it will make the nation more worth defending.

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Biographical Sketch

Leon M. Lederman, internationally renowned high-energy physicist, is Director Emeritus of Fermi National Accelerator Laboratory in Batavia, Illinois and holds an appointment as Pritzker Professor of Science at Illinois Institute of Technology, Chicago. Dr. Lederman served as Chairman of the State of Illinois Governor's Science Advisory Committee. He is a founder and the inaugural Resident Scholar at the Illinois Mathematics and Science Academy, a 3-year residential public high school for the gifted. Dr. Lederman was the Director of Fermi National Accelerator Laboratory from 1 June 1979 to 30 June 1989. He is a founder and Chairman of the Teachers Academy for Mathematics and Science, active in the professional development of primary school teachers in Chicago.For more than thirty years Dr. Lederman has been associated with Columbia University in New York City, having been a student and a faculty member there. Professor Lederman was the Eugene Higgins Professor of Physics at Columbia from 1972–1979 and served as Director of Nevis Laboratories in Irvington, Columbia's center for experimental research in high-energy physics, from 1962–1979. With colleagues and students from Nevis he led an extensive and wide-ranging series of experiments that provided major advances in the understanding of particles and interactions, thus contributing significantly to what is known as the "standard model." Major experiments included the observation of parity violation in decay of pi and mu mesons, the discovery of the long-lived neutral kaon, the discovery of two kinds of neutrinos and the discovery of the upsilon particle, the first evidence for the bottom quark. His research was based upon experiments principally using the particle accelerators at Nevis Labs, Brookhaven and Fermilab, although he has carried out research at CERN (Geneva), Berkeley, Cornell and Rutherford (England). His publications exceed 300 papers and he has sponsored the research of 52 graduate students.In 1990 Profesor Lederman was elected President of the American Association for the Advancement of Science, the largest scientific organization in the U.S. He is a member of the National Academy of Science; and he has received numerous awards, including the National Medal of Science (1965), the Elliot Cresson Medal of the Franklin Institute (1976), the Wolf Prize in Physics (1982), the Nobel Prize in Physics (1988) and the Enrico Fermi Prize given by President Clinton in 1993. He served as a founding member of the High Energy Physics Advisory Panel of the United States Department of Energy and the International Committee for Future Accelerators. In addition, Professor Lederman serves on the Board of the Chicago Museum of Science and Industry, the Secretary of Energy Advisory Board, the Council of American Science Writers, the Weizmann Institute in Israel, and the University Research Association Board. Lederman has received honorary degrees and memberships in over 30 institutions, including England, Brazil, Mexico, Argentina, Italy, Israel, Finland, and Russia.