The Scientific and Technological Importance of Basic Scientific Research

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Many politicians, as well as many spokesmen from industry and academia, are convinced that society should invest exclusively in directed research: activities that are likely to generate direct and specific benefits in the form of wealth enhancement, medical treatment, job creation and improvements in the length and quality of human life. In particular, they believe that the pursuits of such exotic disciplines as particle physics and astrophysics are useless and expensive luxuries; that these disciplines consume resources rather than promoting economic growth and human welfare. For example, let me quote from a recent letter to the Economist: "Fundamental physicists would be hard-pressed to point to anything useful that was directly dependent on their theorising... It is far more important that we encourage our 'best brains' to solve real problems and leave theology to the religious professionals." I believe that these people are sorely mistaken, and that the policies they advocate are unwise and would be counterproductive.

Scientific advances do not always follow preordained plans or painstakingly prepared proposals. Many of the most important discoveries in science were entirely unanticipated. This fact is often ignored by the governments and industries that fund basic research. Science often evolves through intelligent design, but just as often progress results from blind chance. Some people set out to circumnavigate the earth and did just that, but others set out for China and found America instead. The relevant term is serendipity, which derives from a fairy tale called 'The Three Princes of Serendip,' the heroes of which were always making discoveries by accident of things they were not in quest for. So it is with science. Let me give some examples of scientific serendipity from centuries past.

Sir William Herschel is justly famous for his systematic studies of the heavens, and in particular for his discovery of the seventh planet, Uranus. He was the best telescope maker of his time, and may have been the greatest astronomical observer who ever lived. His most significant achievement in physics, however, was entirely fortuitous. In an experiment he designed to ascertain which of the colors of the rainbow carry heat, a misplaced thermometer led him to discover an invisible form of light: heat rays or infrared radiation. For this great and serendipitous discovery, rather than for his more newsworthy sighting of Uranus, an ambitious European space observatory, to be launched in 2007, will be known as the *Herschel Far Infrared Space Telescope.*

On several other occasions, our understanding of electromagnetism depended upon accidental discoveries. Volta developed the electric battery from Galvani's chance observation of the twitching of a severed frog's leg when touched by a bimetallic scalpel. Hans Christian Oersted, while giving a physics demonstration to his class, blundered onto the realization that electric currents produce magnetic effects. Faraday's discovery of the law of electromagnetic induction was also at least partially accidental. None of these scientists recognized the enormous impact their work would have on society.

The last decade of the 19th century saw a virtual explosion of serendipity: the discovery of X-rays by Roentgen, of radioactivity by Becquerel, and of argon and the other inert gases by Rayleigh and his collaborators. None of these scientists discovered quite what they were looking for, nor could they recognize the impact their work would have.

The situation is no different in the other sciences. Frederick Wohler was astonished when he found, quite by accident, that a compound he had synthesized, ammonium cyanate, was identical to the organic substance known as urea. He wrote to one of his vitalist colleagues, "I must tell you that I have prepared urea without requiring a kidney or an animal, neither dog nor man." His discovery closed the seemingly insuperable gap between organic and inorganic chemistry. It ended, or should have ended, the belief in a mysterious vital force lying beyond the scope of the physical sciences. (Here I am alluding to various persistent pseudo-medical practices that continue to affect the credulous, such as Qi Gong, Reflexology, Fen Shui, and others.)

Talks given in Thailand, January 2005.

In 1856, William Henry Perkin was a 17-year-old aspiring chemist. His mentor, the German chemist August von Hoffmann, then visiting England, suggested that Perkin attempt to synthesize quinine from coal tar. Perkin did not and could not succeed in this quest. (Indeed, von Hoffman's challenge was not met for almost another century, until the urgencies of World War II intervened.) Instead of producing the pristine white crystals of quinine, Perkin ended up with a dark, sticky and foul smelling sludge.

But Perkin was a true Prince of Serendip. Noticing that his noxious coal-tar derivative had a purplish tint, he forgot about quinine and abandoned his academic career. He realized that he has solved the age-old quest for an inexpensive and effective purple dye. The enterprising lad set up a factory to manufacture his synthetic dye, which enthusiastic French designers gave the name *mauve.* When England's Queen Victoria and France's Empress Eugénie publically flaunted mauve dresses, Perkin's new dye became so popular that the period became known as the Mauve Decade. As a rich man of 36, Perkin sold his business and returned to academic science, having laid the foundations to synthetic organic chemistry.

And whatever happened to Perkin's mentor? Von Hoffmann recognized the commercial importance importance of Perkin's chance discovery. Inspired by the success of his young protegé, he proceeded to synthesize the second synthetic aniline dye in 1859, calling it *magenta.* Only the historically literate among you will understand why a patriotic German scientist would name his discovery after a battle of that same year at which the French army defeated the Austrians. Subsequently, von Hoffmann returned to Germany where he systematically developed a whole panoply of purple dyes, thereby contributing mightily to his country's primacy in the new industry that emerged from his student's moment of serendipity.

More recently, Alexander Fleming was awarded the 1945 Nobel Prize for his discovery of penicillin. In his acceptance talk, he said: "I might have claimed that I had come to the conclusion... that valuable anti-microbial substances were made by moulds, and that I set out to investigate the problem. That would have been untrue, and I preferred to tell the truth that penicillin started as a chance observation. My only merit is that I did not neglect the observation and that I pursued the subject..." Spoken as a prepared mind in search of unanticipated wonders, here was another Prince of Serendip.

There was a time when companies such as General Electric, AT&T, and IBM played essential roles in the pursuit of truly basic research. In 1928, for example, Dupont's executive Charles Stine argued pointedly that pure scientific research "is bound to result in useful, and in some cases, indispensible knowledge." Ten years later, his vision paid off with the discoveries of nylon (by design) and teflon (by sheer chance). The story of Teflon began April 6, 1938, at DuPont's Jackson Laboratory in New Jersey. DuPont chemist, Dr. Roy J. Plunkett, was working with gases related to Freon refrigerants, another DuPont product. Upon checking a frozen, compressed sample of tetrafluoroethylene, he and his associates noticed that the sample had unexpectedly polymerized into a white, waxy solid that would not adhere to other materials. Teflon remained top secret during the course of WWII, but since then about a billion teflon-coated non-stick pots and pans have been marketed.

Unfortunately, the glory days of commercially sponsored basic research have virtually come to an end. Employees or former employees of the once great Bell laboratories have garnered an amazing eleven Nobel Prizes, but today's much reduced laboratory is unlikely ever to produce another. The Microsoft Company, to give another example, rather than investing in basic research *per se,* has purchased an enormous portfolio of academic patents, which its scientists and engineers are told to exploit. Once again, basic research has been relegated to the universities, whose funding for genuine basic research is ever declining. Instead, the US Department of Energy is pursuing the impossible dream of a hydrogen economy, and even NASA, with its distinguished record of basic research done in concert with university scientists, is now compelled by President Bush to waste its time on the pointless task of sending some poor fool to Mars. I fear for the future of basic science in America.

Had Faraday, Rontgen, and Hertz focussed on the "real problems" of their day, we may never have developed electric motors, medical X-rays and radios. It is true that today's "fundamental physicists" are concerned with more exotic phenomena that are not *in themselves* particularly useful. It is also true that this kind of research is expensive. Nonetheless, I will argue that their work continues to have an enormous impact on our lives. Indeed, the curiousity-driven search for fundamental knowledge is at least as important as the search for solutions to specific practical problems. Ten examples of current day serendipity should suffice to prove my point:

(1) *Informatics:* The World-Wide-Web was created by the physicists at CERN so that the laboratory could transmit experimental data to their collaborators throughout the world. It led to the explosive development of the internet and its countless commercial applications. The 21st century will require a vastly enhanced capability to share, distribute and process vast amounts of data. Once again, it is largely the high-energy physics community that is spearheading the development of a truly Global Grid. This system will tap into computing power at hundreds or thousands of individual computers worldwide to provide ultra-powerful computing services to widely distributed consumers.

The immediate thrust of the Global Grid relates to fundamental experiments in physics and astronomy. However, many important practical applications are easy to foresee and are certain to follow: in other fields of physics, in biology and medicine (such as by sharing genomic and medical-imaging data bases), in climatology, earth and atmospheric sciences (especially for studying global warming and the ozone layer), as well as in engineering, agriculture, epidemiology, global commerce, and education.

(2) *Computers:* Over the last few decades, computers have become essential to life as we know it in a thousand different ways. But the reasons we have computers now and not a century ago is NOT that we have discovered a need for computers. Rather it is because of discoveries in fundamental physics underlying modern electronics, developments in abstract mathematical logic, and the need of nuclear physicists of the 1930s to develop ways of counting particles. Not even the founder of IBM could imagine the role that modern computers play today, and I certainly cannot imagine the role they will play in the future.

(3) *Modern Cryptography* has obvious military applications. However, it also makes possible remote but secure banking and financial transactions. Every time you make a purchase with a credit card or through the internet, you have number theorists to thank. Who would have believed that prime numbers and their study would turn out to have immense commercial importance?

(4) *Global Positioning Systems,* that instantly tell your position and altitude to within a few meters, and have led to a multi-billion dollar industry. These miraculous (and rather inexpensive) navigational systems depend on precise atomic clocks that were developed solely for the purpose of testing Einstein's general theory of relativity. Who would have believed that a theory that was once said to be understood by only a dozen perople would turn out to have immense commercial importance?

(5) *Particle Beam Therapy:* Many so-called "elementary particles," in the form of carefully directed and monitored beams, play essential roles in medicine. It all began—and continues—with X-rays. And it was Madame Curie who first suggested that particle beams could be useful as well.

Beginning in the 1950's, cyclotrons at Berkeley and Harvard that were originally constructed for pure physics research found second careers by pioneering the use of proton beams for cancer therapy. Thousands of patients were helped by these antique accelerators. Today, dozens of dedicated medical accelerator facilities have been constructed worldwide to provide therapeutic beams of protons, neutrons or heavier ions. In addition, high-energy electron accelerators are used to treat certain AIDS-related lesions, skin lymphomas and breast cancers.

(6) *Medical Imaging:* The first medical scanners were developed by high-energy physicists "in their spare time" but not at their own expense. Alan Cormack and Geoffrey Hounsfield shared a Nobel Prize for developing computer assisted tomography. Physicians have come to depend on CAT scanners, magnetic resonance imaging (MRI) and positron emission tomography (PET). MRI uses nuclear magnetism, while PET uses a form of antimatter. Both of these notions arose in an academic milieu far removed from the "real world" problems they have come to address.

(7) *Superconductivity* will underlie many new technologies of the 21st century. A once exotic phenomenon now has many potential applications: to energy generation, storage and transmission, and to transportation, medicine, and electronics. It has been said that "every program in superconductivity owes itself to the fact that Fermilab [a laboratory dedicated to fundamental research in physics] built the (superconducting) tevatron, and it works!"

(8) *Radioisotopes:* Short-lived radioactive isotopes are used on millions of patients each year (including me!) for a wide range of medical purposes: to diagnose disease, to treat various cancers, to alleviate pain, and to perform biochemical analyses of blood, urine or tissue samples for diagnostic or forensic purposes. These isotopes must be produced at hospital-based particle accelerators, or (in some cases) at nuclear reactors sited at government research laboratories.

Long-lived radioisotopes find countless applications through the use of Accelerator Mass Spectroscopy. By means of this procedure, concentrations of a radionuclide as low as one atom in a quadrillion can be measured. This procedure is commonly used in archaelogy, geology, planetary science, and engineering (e.g., leak detection). More recently, AMS is becoming an important tool in medical science (to study the effects of drugs on human subjects, to trace metabolic pathways, etc.). None of this could have happened without research on radioactive isotopes and the development and continuing improvement of sophisticated accelerators and particle detectors.

(9) *Synchrotron Light Facilities:* Electron synchrotrons were developed to explore the underlying structure of matter, an issue that the letter writer I quoted earlier seems to regard as more theological than useful. One of the difficulties in building these machines is that the accelerated electrons lose much of their energy through "synchrotron radiation." However, this difficulty has serendipitously evolved into a multi-billion dollar asset. It turns out that synchrotron radiation is enormously useful for both pure science and commercial technology: for material science, industrial testing, earth sciences, environmental science, life sciences, and for medical diagnosis. About 80 expensive and technologically challenging synchrotron light sources have been deployed. They are sited in 23 different countries throughout the world.

(10) *Neutron Sources:* First discovered seventy years ago, neutrons were immediately recognized as the key to understanding nuclear structure. But who knew how relevant these tiny and unstable particles would become? The discoverer of the nucleus itself remarked that "Anyone believing the atom to be a source of power is talking moonshine." But neutrons have even more to offer than nuclear power. Neutron scattering and diffraction using intense neutron sources have myriad applications to basic and applied sciences and to engineering. So it is that yet another spin-off from fundamental science has led to technological breakthroughs that benefit everyone.

Many of the commercially important developments I have discussed make use of particle accelerators: devices that were invented and developed solely for purposes of pure (and some think, pointless) research. However, today there are some 10,000 accelerators in the world, of which no more than 100 are used for research in nuclear or particle physics.

We mentioned just ten of the many new "spin-off technologies" that were initiated by, or evolved from, or otherwise depended upon the researches of those who have dedicated their lives to contemplating the universe. But there are other good reasons for governments to continue to support seemingly useless undirected research:

• *The Business of Business is Business:* If curiousity-driven research is economically important, why should it be supported by public rather than private funds? The reason is that there are kinds of science which yield benefits that are general, rather than specific to individual products or processes. The eventual economic returns from this kind of research cannot be captured by any single company or entrepreneur. That is why most pure research is funded by governments with no immediate commercial interest in the results. *Government support of undirected basic research must continue if there are to be further technological advances and economic spin-offs.*

• *Guiding Our Governments:* In a democratic society, it is the peoples' responsibility to ensure that their governments adopt rational approaches to address societal problems such as global warming, pollution, hunger, disease, and the depletion of natural resources. For example, how will the energy requirements of modern society be met now that the age of cheap oil is coming to an end? To act responsibly, citizens require a degree of scientific and mathematical literacy far beyond what they have at present. This brings us to my next point:

• *Inspiration of Youth:* Today's ever more technological society depends more on brains than brawn. Scientists and engineers, as well as mathematicians and economists, will play a much more important role in the future than they have in the past. How do we encourage youngsters to be interested in science and math? How do we train enough teachers who are up to this task? Children are naturally curious. They are fascinated by quarks and quasars, black-holes and the Big Bang. Perhaps learning something about the wonders of the cosmos and the marvels of the sub-atomic world can lead them toward useful and productive careers in science and mathematics.

• *The Best and the Brightest:* Particle physicists and cosmologists spend many years developing technical skills or problem-solving modes of thought that can (and often are) redirected toward more practical goals. Many of the industries in Silicon Valley and the Boston area were created by physicists, computer scientists, and accelerator engineers who honed their skills at high-energy physics laboratories. And many of the employees at these (and other!) industries began their careers as researchers in the most pristine sciences. Consider three examples:

(1) *Walter Gilbert,* once a renowned particle theorist, became even more renowned when he turned his attention toward molecular biology. He shared the Nobel Prize in Chemistry for making possible the mapping of DNA; he was the founder of a leading pharmaceutical compamy; he is the leader of the Gilbert Laboratory of Biological Science at Harvard University; and he is an exhibited and respected photographer.

(2) *Alan Cormack and Geoffrey Hounsfield,* whom I mentioned earlier, were high-energy experimenters who shared the Nobel Prize in Medicine for developing the technology underlying computer-assisted tomography.

(3) *Andrei Sakharov* was a brilliant physicist who taught us why there is matter in the universe but very little antimatter. He was also a champion of human rights and the person who convinced the Soviets to sign the atmospheric test ban treaty. He won the Nobel Prize in Peace.

• *International Goodwill:* Scientific research is one of the few areas in which most of the nations of the world cooperate effectively. Indeed, Science has always been a most international endeavor. Copernicus, Brahe, Kepler, Galileo and Newton — a Pole, a Dane, a German, an Italian and an Englishman — taught us our place in the heavens. So it was for the development of all the sciences. Today science, and especially big science, is a truly international endeavor. Here are just a few of many examples: CERNs membership contains practically all the European countries; Super-Kamiokande (where neutrinos were shown to have mass) is a joint Japanese-American endeavor; the CDF detector at Fermilab flies the flags of Italy, Japan and the US. The American Hubble Space Telescope received significant European support, just as Europe's soon to be completed Large Hadron Collider at Cern receives significant American funding. The next great project in particle physics, the International Linear Collider, is likely to be a joint project involving Japan, Europe, and the United States.

The success of the international scientific enterprise can serve as a model for further international collaboration. Let us hope that science and scientists, working in harmony with one another, will lead us toward a century which will be more just and less violent than its predecessor, a century in which the challenges facing humanity will be met, and a century in which all of the peoples of the world can share the marvellous fruits of science and technology.

• *Being Honest:* I have described at length how the most basic and seemingly useless scientific disciplines have contributed, and are contributing, to economic growth & human welfare throughout the world. Long ago, we were warned that pressure for immediate results will invariably drive out pure science, unless deliberate policies are set up to guard against it. This warning is particularly pertinent today. But it must be admitted that pursuits of such disciplines as particle physics, astrophysics and cosmology are not motivated by their potential economic relevance, no matter how great that may be. *We study these disciplines because we believe it to be our duty to understand, as best we can, the world we were born to.* Science provides a rational understanding of our place in the universe and can replace the destructive superstitions of the past. I believe it to be of profound cultural and philosophical importance for us to know such things as:

How the Universe began in a Hot Big Bang which led to the creation of billions of galaxies each containing billions of stars.

How stars are born, evolve and die, and what makes them shine.

How our enormously successful “theory of almost everything” still cannot identify the mysterious dark matter and dark energy that seems to surround us, nor explain why the basic building blocks of matter are what they are.

There is so much more to be learned! Science is truly the greatest story ever told! Let it continue!