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Basic Research and a Moral Responsibility of Scientists

Daniel Kleppner

Massachusetts Institute of Technology

Cambridge, Massachusetts, U.S.

The history of the living world is an elaboration of ever more perfect eyes in a cosmos in which there is always something new to be seen.

Teillard de Chardin

Teillard was a paleontologist, geologist, philosopher and Jesuit priest; his epigram provides a stunning description of the evolution of science. Teillard's phrase "ever more perfect eyes", for instance, accurately describes the evolution of telescopes from the crude optical devices at the dawn of the 17th century to today's space telescopes. This fabulous development was driven by curiosity about the nature of the universe, which is to say that it was the product of basic research. I would like to discuss issues related to basic research in the physical sciences that relate to the central concern of this session of the Pontifical Academy of Sciences. By "basic research" I mean research motivated by the joy in understanding nature in contrast to solving a particular problem. When Teillard talked about "ever more perfect eyes in a cosmos in which there is always something new to be seen", he was talking about basic research

Einstein's search for a theory of gravity – his General Theory of Relativity – is an iconic example of basic research. The problem he struggled to solve – to create a theory of gravity that avoided some inconsistencies in Newton's theory of gravity – worried hardly anyone else and had no conceivable use, at least not at that time.

A startling consequence of Einstein's theory is that gravity affects time. A clock on top of a mountain runs faster than an identical clock at sea level, but not by much: a clock on the peak of Mt Everest should run fast only by about a millionth of a second a month.

The quest to observe Einstein's prediction for the effect of gravity on the rate of a clock has a remarkably well documented starting date: January 11, 1944. That day, a New York Times article carried the headline "Cosmic Pendulum for Clock Planned". It was the report of a speech at an American Physical Society meeting in New York City, by I. I. Rabi, a physicist at Columbia University. Rabi proposed creating a clock whose ticks were governed not by the swing of a pendulum but by pulsations within an atom that could be measured by a technique he had invented: molecular beam magnetic resonance. The accuracy of such an atomic clock could be fabulously high. The NY Times article reported that "Professor Rabi said that he would like to see someone build an atomic clock that would be capable of providing for the first time a terrestrial check on the Einstein postulate that the gravitational field produces a change in the frequency of radiation".

The creation of atomic clocks sprung directly from the quest to see whether gravity affects the rate of a clock, that is, whether gravity affects time. Lacking any other conceivable application for such an accurate clock, the quest provides an ideal example of basic research.

Nobody rushed to build an atomic clock following Rabi's talk in 1944: the research establishment was in disarray from World War 2 and there was a technical barrier. That barrier was breached in 1949 when Norman Ramsey, a former student of Rabi's who had just joined the physics faculty at Harvard University, proposed a technique with the cumbersome name of "the separated oscillatory field method". Serious work on an atomic clock started then and in 1954 the first experimental clock was demonstrated in England. It came to be known as the cesium beam atomic clock.

In 1953 I went to Cambridge University, England, with a two-year Fulbright Fellowship. My tutor, Kenneth Smith, did something tutors generally did not do at Cambridge in those times: he talked with me about his research. His work centered on studying the properties of atomic nuclei using Rabi's technique. Smith told me about Rabi's proposal to observe the effect of gravity on clocks. I remember being stunned by the idea that gravity affects time but I could only store the thought among the clutter of possibly interesting ideas rattling around in my head.

In September 1955 I entered graduate school at Harvard University. Ramsey was on the faculty and the following spring I joined his group. In the fall of 1956 he told me about his idea for the hydrogen maser, a

frequency standard fundamentally different from the cesium frequency standard but which had some potential advantages. Naturally, I jumped at the opportunity. The first hydrogen maser was demonstrated in August 1960.

When Rabi proposed that “somebody ought to build a clock”, he was referring to what became known as the cesium-beam clock. The first cesium clock was demonstrated in 1956 and within a few years a practical device had been produced. The hydrogen maser is comparable in accuracy to the cesium beam clock and most time standards laboratories have one or more.

Although the hydrogen maser was created specifically to verify Einstein’s conjecture about time and gravity, its unanticipated applications are noteworthy. The hydrogen maser made the radio-astronomy technique known as Very Long Baseline Interferometry (VLBI) possible.

VLBI allows astronomers to make radio telescope antennas that are effectively the size of the earth. VLBI enables astronomers to create maps of hydrogen in the universe with astonishing detail, and allowing them to look further back in time than by any other technique. Recently progress has been reported on the Event Horizon Telescope. This telescope combines data from about 15 radio telescopes around the world. Working together, these are powerful enough to make an image of the event horizon as matter disappears as it falls into the massive black hole at the center of our galaxy. Once inside the event horizon, material disappears forever but as it falls in it radiates intensely. Images of that radiation make it possible to study the predictions of General Relativity under conditions never previously observed.

The greatest impact from the development of atomic clocks, however, is the creation of the Global Positioning System (GPS). The GPS is a technical marvel of the Space Age. It is fundamentally a timing system and atomic clocks are at its heart. General Relativity is also at its heart: GPS would not work if Einstein’s theory of gravity were ignored. To my knowledge, nobody had thought about such a system before atomic clocks became a reality and nobody could have imagined the powers of today’s GPS.

Today the GPS is ubiquitous: it is at the heart of the air control systems that guide planes in flight and the navigational systems in smart phones and automobiles. The GPS keeps our communication networks and power grids synchronized. It is crucial for medical emergency systems. Above all, the GPS is crucial for understanding the existential threat to humanity that is the focus of this Plenary Session: Climate Change.

Understanding the global climate requires data on a vast number of variables: radiant energy flow to and from Earth, vertical and horizontal temperature profiles, cloud covering and temperature, sea and land surface profiles, ocean surface temperature and wind speed, global precipitation, water content of the atmosphere and troposphere. The list goes on and the data are enormous.

The primary source of data on Earth’s climate is a fleet of eight weather satellites in polar orbits, four from the U.S., and four from the European Space Agency. This fleet scans the entire surface of Earth four times a day. Often, the satellites work together in pairs, exchanging radar and lidar (“light radar”) signals to look through the troposphere to measure its water content. This particular measurement is crucial to a global analysis because most of the atmospheric water is stored in the troposphere. In addition to the polar fleet of weather observatories, there are clusters of synchronous satellites from various nations that continuously view Earth. The U.S. has two clusters viewing the entire country; one extending to points east, the other to points west.

Because hardly any of these global climate measurements would have been possible without GPS, it is valuable to keep the origin of the GPS in mind: mere curiosity about General Relativity. Basic research was the driving force for the GPS it is often the driving force for transformational advances, advances that broadly affect society.

Here are two other examples of transformational discoveries from basic research:

The invention of the maser and the laser by Charles H. Townes originated in his research on the temperature of molecules in space. His research contributed to the discovery that space has a temperature and that discovery triggered a revolution in cosmology. To measure the feeble signals of molecules in space, Townes invented a new type of molecular signal amplifier called the *maser* (the acronym for *microwave amplification by stimulated emission of radiation.*) Townes and his colleagues then extended the maser concept from microwave frequencies to optical frequencies, which led to the invention of the laser (acronym for *light amplification by stimulated emission of radiation.*

The laser has transformed communications, manufacturing, and lighting. Lasers can be found in essentially every scientific and industrial research laboratory. Applications range from lidar systems at the heart of automobile collision avoidance devices to surveying systems that monitor Earth strains in volcanic and earthquake-prone areas.

Nuclear magnetic resonance (NMR) provides a second example of basic research generating a transformational technology. NMR was invented independently by Felix Bloch at Stanford University and

Edward M. Purcell at Harvard University. NMR was invented primarily to study the properties of atomic nuclei but it quickly became an essential tool in chemistry. The major impact of NMR came about twenty-five years after its invention when powerful computers had become practical. Combining these technologies led to the invention of Magnetic Resonance Imaging, (MRI) by Paul C. Lauterbur in the U.S. and Sir Peter Mansfield in England. MRI makes it possible to take non-invasive pictures anywhere within the human body. It is now a standard imaging technique.

I stress these unexpected rewards from basic research because society urgently needs new ways to deal with the ominous threats of climate change. Research on many aspects of energy production and usage is underway but I want to emphasize the importance of new ideas coming from basic research unrelated to any perceived need.

There is no way to predict which area of research will suddenly bloom and possibly create a transformational technology but the conditions for such discoveries are well known: a research environment in which the search for new knowledge is respected, research is supported, and institutional structure encourages communication and collaboration.

Today, in the United States, support for basic research is dwindling. Opportunities for a career in basic research are decreasing and our ability to attract excellent students from home or abroad is declining. When considered in the context of the most recent report of the Intergovernmental Panel on Climate Change (IPPC), neglect of basic research could be disastrous.

It has been known for decades that there is a possibility of a runaway situation in which an increase in global temperature feeds back to accelerate the global heating. The process could lead to a massive change in climate and a catastrophic elevation of sea level. The latest report of the IPPC concludes that previous reports erred in being too cautious: the time to stem the flow of greenhouse gases is shorter than had been estimated. We are facing a truly existentialist threat to civilization. New technologies need to be fostered, but in the rush to develop them a reasonable level of basic research must be maintained if we are to hope for new transformational technologies.

Vigorous international leadership is required if we are to make a rapid change in greenhouse gas emission. The United States should be capable of leading but the current President of the United States is opposed to science and mocks the concept of scientific truth. He and his followers take comfort in a policy of denial. Denial is guaranteed to make matters worse. Until the U.S. recovers its moral bearings we will continue to waste the precious short time we may still have for effective action.

This creates a personal dilemma that I imagine many scientists share with me. Ever since the creation of the atomic bomb there has been a tradition of scientists involving themselves in science policy and public affairs. In the U.S. the list from physics includes Leo Szilard, Eugene Rabinowitch, Hans Bethe, I.I. Rabi, Viki Weisskopf, and Richard Garwin, as well as organizations such as the American Association of Atomic Scientists and the Union of Concerned Scientists. How can scientists honor that tradition today?

If our civilization succeeds in learning how to live in harmony with the natural world, science will have played a crucial role in the transition. The immediate problem in the United States is to convince Congress of the urgency of the situation. Happily, the years of developing STEM education in the U.S. are starting to pay off. There is a growing number of scientifically literate citizens and members of Congress. These people will listen if scientists speak up. Speaking up for science is surely high on the list of the moral responsibilities of scientists today.