Future of Science and Society

DOI: 10.1002/anie.201206738

1999

Science for the "Haves"

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basic research · curiosity · history of science · science funding

More than a decade ago, one of us wrote a commentary titled "*Science for the Have-Nots*".[1] The author (A.Z.) was and continues to be concerned about the unhealthy state of education and science in the developing world. It was advocated that major reforms of the governing systems, aided by a new type of partnership between the developing world and the developed one, is needed in order to change the plight of the 80% world population of have-nots. In this Essay, on this special occasion, we raise a concern about the state of education and science in the countries of the haves—the developed world—and we believe that reform in this case simply requires a return to the policy of wise investment in basic science, the endless frontier.

Only one-fifth of the world's population enjoys the benefit of life in the developed world and the gap between the haves and have-nots continues to increase, threatening stability. The World Bank informs us that of the 7 billion people on Earth, 5.75 billion live in developing countries; 2.4 billion live on less than US$2 a day; 0.81 billion people still do not have access to an improved water source; and 1.28 billion live on less than $1.25 a day, which defines the absolute poverty standard. Additionally, 1 billion people suffer from hunger today.

Globalization, in principle, is believed to help nations prosper and advance, but in reality, it is better tailored to the fraction of the world's population able to exploit natural resources and markets. The disparity is huge. The per capita gross domestic product—the total unduplicated output of economic goods and services produced within a country as measured in monetary terms—has reached $50000 in some Western countries compared to about $1000 in many developing countries, and significantly less in underdeveloped populations. According to World Bank statistics, Egypt's GDP is US$2800 and South Africa's is US$8100 while South Korea is at US$22400, and the United States is at $48400. It is understood that disparity in productivity will always exist due to differences in culture, work ethics, and political systems, but new partnership programs are imperative in order to encourage global benefits and discourage global instability.

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For developing nations, the barriers to achieving developed-world status are many. High rates of illiteracy in some developing countries reflect the failure of educational systems and are linked to the alarming increase of unemployment. Second, the limited and ineffective use of human capital—largely due to strong seniority-based systems, nepotism, and the centralization of power that thwart opportunities for advancement—results in suppressed thought and stifles human potential. Third, the intermingling of state laws and religious beliefs causes confusion and chaos through the misuse in politics of the fundamental religious message of ethics and morality. And fourth, there is no coherent vision for education and science policies.

The developed world is now facing problems of similar magnitude but the problems are different in origins and solutions. One critical problem is the change in the state of education and scientific research. After the Second World War, scientific research was well supported: in the 1960s, for example, the sky was the limit, certainly in the U.S. One of the authors (A.Z.) benefited greatly from the conducive atmosphere for curiosity-driven research, and during this time his research at Caltech began with a funded proposal submitted to the U.S. National Science Foundation. The research described there was esoteric by today's standards, proposing to examine the coherence of atoms and molecules—a subject that was to be explored out of sheer curiosity. The truth is that the investigator did not plan for this research with the broad impact on society in mind; that is impossible to foresee. This research was the foundation for the work that led to the 1999 Nobel Prize in Chemistry for the development of *femtochemistry*. It is doubtful that this same research proposal would be funded today.

At present, the situation is different as a result of major changes in the funding policy of basic research and in the principles governing the quest for new knowledge. Because resources are limited, universities and research institutions have been forced to reorient their missions more towards profit making. Surely, the ultimate benefit of useful knowledge is to serve society's needs, but as history tells us most paradigm-shifting innovations come from researchers' curiosity about natural phenomena, and in many cases scientific discoveries have been made through serendipity. Even the most distinguished researchers cannot predict the path to the next discovery or the most important innovation. Unpredictability is the fabric of scientific discovery.[2]

We are both connected to Caltech academically and have observed at least two generations of researchers and students.

It is clear that the majority of those who strive for an academic career are driven by the excitement of research. These aspirations are then fostered by the values and knowledge derived through a good education system and by government and society's appreciation of the importance of education and science. In general, young people choose science and engineering as a profession, in academia or industry, because they can acquire new skills and learn the rational scientific thinking required for solving problems. In return, they expect a decent job.

Today, finding employment in, for example, chemistry, has become challenging. In fact, according to the most recent American Chemical Society survey of new graduates in the U.S., unemployment in chemistry reached a record high. Due to economic forces and recent trends in the pharmaceutical industry, many PhD chemists are holding temporary or non-chemistry-related positions or are unemployed. In addition, the average age at which principle investigators in the United States receive their first Research Project Grants (R01 awards) from the U.S. National Institutes of Health has increased to 42 years.[3] This is related, at least in part, to the increased average age at which investigators obtain their first academic appointment, and multiple postdoctoral positions are often becoming necessary. Needless to say, these obstacles and postponements may discourage young people from pursuing an independent career in a research environment.

Industrial research labs have, for the most part, redirected their resources and efforts into applied research areas relevant to their market products. One jewel from earlier times was Bell Labs. At Bell Labs, fundamental research was so advanced that it used to be said it was "the best university in America." Numerous scientific discoveries and inventions were made there, including the transistor, which is the most basic unit that triggered the digital revolution. Bell Labs employed some of the world's best scientists and engineers and collectively they have had stellar impact on discovery and invention. The list included Nobel laureates Charles Townes, William Shockley, John Bardeen, Arno Penzias, and Robert Wilson, and the topics varied from masers and lasers to superconductivity and cosmology. Sadly, this structure for broad-based, curiosity-driven research at Bell Labs no longer exists.

Even in academia, curiosity-driven research is often looked upon unfavorably. Research proposals have to address "broad relevance to society" and provide "transformative solutions" even before research begins. In today's proposals, the number of pages dedicated to funds management, broad impact, and societal implications is significant, and in some cases dominant, when compared to the number of pages focusing on the science itself. Universities are increasingly pressured to raise funds for annual costs and overhead is on the rise. Professors are chasing funds and writing more proposals; the available time for creative thinking is reduced and the numbers of academics involved in commercial enterprise is increasing. Faculty tenure at universities is often determined by how much money young faculty members have managed to raise. These constraints and practices beg the question: Would a young Maxwell, Pauling, or Crick today be attracted to their professions, and would they be able to pursue their inquiries into fundamental questions in the current environment?

For centuries, curiosity in science has led to discoveries and innovations, and this "old-fashioned" approach has had a proven impact on science and society. Quantum mechanics, relativity, the Big Bang Theory and the origin of the universe, and the deciphering of the genetic code are discoveries made along this path, and so are the inventions of revolutionary technologies such as the laser (conceived by asking how light can be amplified), MRI (developed from curiosity-driven research about spinning electrons and nuclei), and the transistor (discovered as a result of curiosity about the nature of electrons in semiconductors), not to mention the huge progress made in the chemical industry, the pharmaceutical enterprise, and the agricultural sector. The manufacturing, medical, and digital IT industries that followed now constitute the backbone of global communications and the economy. From the cell phone to Google's and Apple's global markets, basic knowledge derived from curiosity-driven research is the springboard of their developments.

What is clear is that progress in research requires the nurturing of creative scientists in an environment that encourages interactions between researchers and collaborations across different fields. But such a nurturing atmosphere cannot and should not be orchestrated by weighty management, as creative minds and bureaucracies are inharmonious. Today, officials in many developing countries are seeking mechanisms to reach the innovation level of the developed world, but the core principles of innovation are often misunderstood. Regrettably, the same trend is creeping into developed countries.

One must then ask, is there a formula for "managing discovery making?".[4] The answer is in the realization of and belief in the natural evolution of developments, from basic research to technology transfer, and then to societal benefits. For basic, fundamental research to flourish, three elements cannot be forgotten. First, and most important, are the people involved. A proper education in science, technology, engineering, and math (STEM) is essential, and the search for the most creative minds for carrying out research is the key for success in R&D. Large buildings, and even massive funding, alone will not lead to significant progress without such people.

Second, nurturing an atmosphere of intellectual exchange is of paramount importance for ideas to crystallize. The distraction for faculty of either writing extensive and numerous proposals or becoming business-like managers is the beginning of the end. There are serendipitous innovations that are made by a single person, or a group of researchers, but most discoveries and revolutionary ideas are a result of individuals having the time to think and interact with other researchers. Consider how quantum mechanics, a major force behind innovations in the world economy, came about over two decades of work and by great curiosity-driven thinkers, such as Planck, Bohr, Einstein, de Broglie, Schrodinger, and Heisenberg.

Third, even the most creative mind can achieve little without resources. Obviously, investment in science is required to acquire new instruments and to hire competent staff. Countries and institutions that provide the proper infrastructure and the funding for new ideas will be the home of new discoveries. However, such support should follow the vision of creative researchers, rather than be based on the development of centers built to lure money or follow research fads. There are several examples of institutions of discovery in the developed world and in every case we see a correlation between the quality of the researchers involved and the significant discoveries made. Think of the Cavendish Laboratory in Cambridge under the leadership of J. C. Maxwell, J. J. Thomson, and L. Bragg and the discoveries that resulted there and changed the world: the electromagnetic nature of light, the discovery of the electron, and the development of X-ray diffraction. Caltech is another example; we find it remarkable that an institution with less than 300 faculty members in all disciplines is able to produce from its faculty and graduates 35 Nobel laureates. The key to these achievements is the R&D milieu that has flourished there from its inception, and that still attracts the best minds.

The correlation between investment in basic research and innovations that impact economies and societies is clear across the globe, from the U.S. after World War II to China today. In the 1950s, Robert Solow (1987 Nobel Prize in Economics) showed that new technologies create a large portion of economic growth, affecting nearly 75 % of the U.S. growth output. The theory of quantum mechanics alone continues to have major impact on world economy as without it revolutionary technologies would not have been realized. Think of the laser and the optical communication industry, MRI and the health industry, and the transistor and the IT market, not to mention the vast progress made in drug discovery, gene technology, and miniaturization. Vannevar Bush's vision of science as the endless frontier[5] is indeed the one vision legislators should keep in mind when deciding on funding policy of basic research, innovations of tomorrow, and economic prosperity.

Sunday August 5, 2012 marked the historic rover landing on Mars; this triumph demonstrated the accumulated power of innovation in the U.S. It is fitting that the one-ton, car-like rover begat by curiosity bears its name—*Curiosity*.[6] Over the coming two years it will reveal unknowns of our nearby planet. This quest for knowledge of the unknown is what science is all about, and is how the developed world acquired its power of innovation. Some developing countries are realizing this power of science, investing generously to transform their economies, and the progress is evident. Equally important is their investment in science education. At the 2012 International Chemistry Olympiad, the team from South Korea emerged as the top performer among 72 countries in the event held in the U.S.; according to C&EN magazine, "*members of the U.S. put on a solid performance*".[7]

Since the Industrial Revolution, the West has dominated world politics and economics principally due to the power of science, but it would be hubristic and naive to think that we now know what is relevant for tomorrow. Investing in education is investing in the future. For the past five centuries the West has had the right ingredients for achieving progress through such investments in useful knowledge. Now it is time to return to this wise vision, perhaps with a new intra-national partnership between government, industry, and research institutions. If not, a transition may be in the making, with the sun of innovation rising from the East.[6]

Epilogue: The Genius of Science

Everyone knows the value of the Nobel Prize, but perhaps many do not know what is engraved on the other side of the medal bearing the famous portrait of Mr. Alfred Nobel. The medal was designed by Erik Lindberg in 1902 to represent Nature in the form of a goddess resembling Isis—or eesis—the Egyptian Goddess of Motherhood, Nature, and Magic (Figure 1). She emerges from the clouds, holding a cornucopia

Figure 1. Reverse side of the Nobel Prize medal.

in her arms and the veil which covers her cold and austere face is held up by the Genius of Science.[8] The inscription reads: "*Inventas vitam juvat excoluisse per artes*" (from Vergil, loosely translated as "And they who bettered life on earth by their newly found mastery"), with the official translation here "*Inventions enhance life which is beautified through art*". Indeed it is the genius of science which dispels the darkness of ignorance and lightens human lives for generations to come.

Received: August 20, 2012
Published online: December 3, 2012

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