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The Challenge in Frontiers of Science and Technology

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§ 1 Introduction

It is a great honor and pleasure for me to be invited to give a talk at the celebration of Einstein's "miraculous year", organized by the Bibliotheca Alexandrina, the heir to the famous ancient Library of Alexandria.

§2 Modern Civilization

- Challenge to Limits of Human Faculties

Our modern civilization indeed created an elaborated artificial environment by providing the large number of tools, instruments and machine that surround us. Thus, most of our physical labor has been replaced by a variety of machines and, more recently, most of our routine brainwork is being replaced by information processing systems.

Looking back over the course of development of the civilization, history clearly shows that our forefathers "pushed the limits of human faculties."

Firstly, man invented various devices and machines that broke through the pre-existing limits to the amount of physical work that one person could do. These new devices significantly expanded our productive potential. One can move faster and handle bigger loads with machines, which usually require a good deal of energy consumption.

Supplying this energy spurred the development of technologies in many fields such as mechanical engineering, material engineering, electrical engineering, civil and military engineering.

Secondly, through the use of their intellect, human beings have greatly enhanced their capacity to process information. "Challenging the limits of our mental faculties" has given birth to the computer. It continues to drive us to exploit the immense potential of information technology. We have witnessed remarkable advances in the data processing power of computers and in the related field of artificial intelligence. When we can harness the potential of the petaflop supercomputer we will be able to do things with computers that hitherto could be done only by the human brain.

Thirdly, our growing understanding of the genetic code, DNA, and its implication, has created the potential to live a longer and healthier life. Clearly, we are "challenging the limits of human longevity" in the epoch-making field of biotechnology. Starting with cancer, various lifestyle-related diseases could be genetically understood and treated in a manner that is tailored to the DNA of each individual. If this approach to fighting disease could be realized, without a doubt we would be able to further reduce the threat of disease and lengthen the human life span. Biotechnology is trying to find alternatives to the extremely slow evolutionary process not only to enhance human health but also to lengthen the life span. It is challenging the laws of nature. In this sense we are engaged in startling developments that are unparalleled in human history.

The desire to see, understand, design and fabricate tiny nanometer-scale objects is at the heart of "challenging the limits of smallness" that created the active field of nanotechnology.

§3 Nobel Prizes – Challenge to Limits of Science

Out of many prizes, the Nobel Prize, which started in 1901, is the world's most prestigious award. Through Nobel awards, we can see "how researchers are challenging the limits of science and technology". For example in 2001, the Nobel Prize for physics was awarded for the achievement of the Bose-Einstein condensation, which was due to a challenge to the previous limits of attainable low temperatures. In 2002, Prof. Koshiba received the Nobel Prize for his pioneering contribution to astrophysics, which arised from a challenge to the limits of the sensitive techniques necessary for the detection of neutrinos. In the case of the Esaki Tunnel Diode, the Nobel Prize was awarded for the experimental discovery of quantum-mechanical electron tunneling in p-n junctions being as thin as 10 nanometers. At the time, this was a groundbreaking thinness which could be said to have been a challenge to the limits of thinness of semiconductor junctions.

There is no doubt that science and technology have made invaluable contributions to improve our general living conditions. However, nobody can dispute the negative side of their success. To cite an example, nuclear weapons present enormous threat to the whole world. The most negative outcome of the modern scientific civilization is probably its extraordinary serious impact upon the environment. The most harmful effects include carbondioxide emissions, which are the main culprit in global warning, and other forms of environmental pollution.

In 1995, three scientists, Paul Crutzen, Mario Molina and Sherwood Rowland received the Nobel Prize for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone. The unnoticed release of chlorofluorocarbon used in refrigerators was apparently responsible for the depletion of the ozone layer, which led to undesirable increase of ultraviolet radiation on the ground. Their award attracted attention from around the world as research into the global environment has benn recognized with a Nobel Prize for the first time.

§4 Personal History

Please allow me now to introduce my personal history of Four Seasons as follows:

(1) 1925 - 1947 "Childhood and Adolescence"

I was born in Osaka, and then lived in Kyoto until finishing a high school. I then moved to Tokyo, and graduated from the University of Tokyo in 1947.

(2) 1947 - 1960 "Youth"

I started to work at Kobe Kogyo Corporation where I

stayed until I joined Sony in 1956. There, I developed the Esaki Tunnel diode in 1957, which was to be my Ph. D thesis at the University of Tokyo, later for which I was awarded the Nobel Prize in Physics (1973).

(3) 1960 - 1992 ”Life in New York”

I moved to the United States where my discovery of the diode was highly appreciated. In 1960, I joined IBM T. J. Watson Research Center, New York, where I pioneered “designed semiconductor quantum structures or man-made superlattices” and opened up a new frontier in the field of semiconductors, later for which I was awarded the Japan Prize (1998).

(4) 1992 - Present “New Life in Tsukuba and Tokyo”

When I was voted President, University of Tsukuba, I returned to Japan and found a new leash of life in Tsukuba in 1992. I finished President, University of Tsukuba in 1998 and subsequently assumed President, Shibaura Institute of Technology, Tokyo from 2000 to 2005. Meanwhile, I have been keeping the position of Chairman, Science and Technology Promotion Foundation of Ibaraki since 1998.

It was in 1947 that I completed my studies in the Physics Department of Tokyo University and moved on to life as a researcher on vacuum tubes at Kobe Kogyo Corporation, a company which no longer exists because of financial failure. Coincidentally, 1947 was the year in which the epoch-making transistor was invented at Bell Telephone Laboratories.

I moved into semiconductor research at that early stage because the transistor appealed to my spirit of inquiry. So, in 1956, I joined Tokyo Tsushin Kogyo, the forerunner of Sony Corporation. Tokyo Tsushin Kogyo was then a small venture company. I found a free and innovative atmosphere of the company very attractive. In retrospect, the company was in many ways an ideal model for new ventures.

We learned that success and failure may follow each other. Success could lead to failure because sometimes people become over-confident with success and may defy their rational judgements. On the other hand, failure could lead to success because failures may serve as stepping stones towards creative solutions to open up frontiers.

Looking back, the decade of the 1950s was quite remarkable as a period of technological innovation in the field of electronics: The radical change from vacuum tubes to transistors soon led to vast improvements in the performance of virtually all electronic products, including consumer-oriented goods, telecommunications and data processing. In fact, it is no exaggeration to say that today's information-oriented society was made possible by the process of technological innovation initiated in the 1950s.

I myself was extremely fortunate to have started my career in the midst of such a period of technological innovation. The stimulating environment certainly encouraged me to carry out the thesis work on the Esaki Tunnel Diode in 1957 for which I was awarded the Nobel Prize in Physics in 1973.

I visited Europe for the first time to present a paper at an International Conference on Solid State Physics in Electronics and Telecommunications held in conjunction with Brussels Expo 1958. William Shockley, Nobel Laureate in physics, gave the keynote lecture in the opening session of the conference. Since he had referred to my research work on the Esaki diode, a large audience was attracted to my presentation on the Esaki Tunnel Diode at the conference later in the week.

After Europe, I traveled to the United States and visited the Bell Telephone Laboratories where the transistor was born. Let me read you the words which appear below the bust of Alexander Graham Bell, the Scottish-born American audiologist best known as the inventor of the telephone, which stands in the foyer of the main entrance to Bell Laboratories: "Leave the beaten track occasionally and dive into the woods. You will be certain to find something that you have never seen before."

§5 Judicious Mind and Creative Mind – Einstein's Creativity

The invention of the transistor is among the most remarkable technical achievements of the 20th century. That example of technological innovation taught us an important lesson. The transistor is substantially different from the vacuum tube, and no amount of research and improvement of the vacuum tube could have led to the birth of the transistor.

There is a tendency, especially in mature and stable societies, to assume that the future will simply be a natural and linear extrapolation of the past through the present. However, nowadays it is scientific breakthroughs and technological innovations that shape and form the future.

The UNESCO has declared this year, 2005, the International Year of Physics, in celebration of the 100th anniversary of Albert Einstein's "miraculous year" in 1905 when he published multiple seminal papers describing ideas that marked the change from classical to modern physics.

These ideas were born, not under the leadership of prominent figures in the academic community, but through exchanges with young cosmopolitan friends in a climate filled with revolutionary ideas.

Einstein's amazing intelligence pin-pointed core issues in the world of physics at that time, skipping over peripheral problems and unflinchingly challenging ideas to find out answers.

It may be a surprise to learn that Einstein was only 26 years old in 1905. But it also might be this very youth that made him challenge existing ideas and achieve creative results. Einstein's theories forced changes from conventional ideas in the world of physics.

Science, as developed in the age of the Renaissance, instilled scientific and rational thinking in the minds of

Western Europeans in struggles against religion and conservative ideology. It had a profound effect on the modernization of Western Europe, including the French Revolution.

The power of the human mind can be divided into two major categories. One is the power of the judicious mind which allows us to analyze, understand, select and make fair judgements. The other is the power of the creative mind which allows us to create new ideas through the activity of the intellectual imagination. It is this form of intellectual creativity that provides the engine for progress and that has stimulated and sustained the advance of human civilization.

If we say that creativity is individualistic and represents the challenge of the future, then the judicious mind can be said to have a non-individualistic aspect and to be essentially concerned with the body of existing knowledge.

I would like to state here my arbitrary assumption regarding the dependency of age in terms of the two different strengths, regardless of individual differences.

Let's say we work from the age of 20 to 70, and on a scale of zero to 100, the capability of the creative mind is at 100 at the age of 20. Now let's say this strength declines with age to eventually tap out at zero at the age of 70. Meanwhile, the strength of the judicious mind is zero at the age of 20 and increases with age to reach 100 at the age of 70.

Given these conditions, declining the creative mind and rising judicious mind become equal at the age of 45. But the two forces can also clash with each other at that time to bring about a midlife crisis.

Einstein said he had no special talents. He said he only had a strong curiosity that obsessed him. And curiosity is probably the other dominant quality found in young people along with creative strength.

In Japan, there are many expressions that take a harsh view of youth, including "wakage no itari," (youthful indiscretion.) But we have to appreciate the performance of the young for the sake of scientific and technological development and the advancement of start-up businesses, as well as many other adventurous issues.

§6 Superlattice Research - Challenge to Nanotechnology

In 1960, I decided to leave "Japanese beaten track" and moved to the United States, accepting an offer from IBM T. J. Watson Research Center, New York. I was fortunate to have found a first-rate research environment where my studies sometimes proved fruitful.

In 1969, research on "man-made quantum structures" was initiated with Esaki and Tsu's invention of a semiconductor superlattice. The lattice constant of this superlattice is in the range of 1-10 nanometers, substantially longer than that of the host crystal but shorter than the electron phase-coherent length. This invention was perhaps the first proposal to advocate the engineering of a new semiconductor material by applying the advanced growth technique of MBE, after designing the structure in accordance with the principles of quantum theory in such a way as to exhibit desirable optical and transport properties, including Bloch oscillations. Since this invention offered a new degree of freedom in research, rather like making a "gedanken-experiment a reality, many ingenious studies were inspired.

Esaki and his coworkers' pioneering research on superlattices and quantum wells in the 1970s and 1980s triggered a wide spectrum of experimental and theoretical investigations resulting in not only the observation of a number of intriguing phenomena (differential negative resistance, high electron mobilities, large excitonic binding energies, large Stark shifts, distinct Wannier-Stark ladders and Bloch oscillations), but also the emergence of a new class of transport and optoelectronic devices (high electron-mobility transistors, HEMT, high-speed resonant tunnel diodes, high-performance injection lasers incorporating quantum wells and new unipolar lasers such as quantum cascade lasers).

Abundant new physics was brought about by the introduction of the man-made superlattice which has been one of the most keen subjects in the field of advanced semiconductor research. It should be pointed out that the true meaning of the Wannier-Stark states of an election in a periodic potential plus homogeneous field including Bloch oscillations (the macroscopic quantum effect), was one of the long-standing problems of single-particle quantum mechanics. The beginning of the study of this problem dates back to the paper by Bloch (1928), followed by Zener (1934), Landau, Wannier, Zak and many others. The introduction of semiconductor superlattices gave a decisive impact on the problem. The unambiguous observation of the Wannier-Stark spectrum and Bloch oscillations is a historical event which finally ended a long theoretical debate about the nature of the Wannier-Stark states and now it is commonly accepted that they are the resonant states of the system.

Excerpts from the Superlattice Story prepared in 1998 by US Army Research Office are as follows: The superlattice concept proposed under Army sponsored research triggered a revolution in solid state physics. …… The impact of Esaki's research has been profound. The superlattice concept precipitated more than 10,000 publications and is directly involved in some 465 patents in the U.S. alone. …… The superlattice may be regarded as the trunk of a genealogical tree of quantum effect devices, …… The characteristic dimensions of superlattice devices certainly served as the precursor of today's "smaller and smaller" nanotechnology emphasis.

After 32 years in the United States, I returned to Japan. At that time, I made the radical transition from being a researcher in a corporate setting to holding a position in education as the president of a national university.

§7 Knowledge Societies

Our global information society is moving towards knowledge societies when the progress of civilization increasingly hinges on intellectual creativity of new knowledge.

Knowledge can be classified into the following four categories according to its purpose:

1. Knowledge for opening frontiers:
   innovative or basic sciences
2. Knowledge for society's infrastructure:
   social sciences, engineering, etc.
3. Knowledge for individual humans:
   humanities, medical sciences, life sciences,
   health & sports sciences, etc.
4. Knowledge for human survival and security:
   environmental sciences, resources & energy sciences, international relations, etc.

The stimulation of the nation's socioeconomic systems and a strengthening of its international competitiveness can be achieved with an enrichment of its intellectual property as well as resources. In light of this, universities are playing a major role in addressing these challenges.

Three objectives of universities are as follows:

1 Research to create new knowledge

2 Education to provide students with systematized knowledge
3 Application of knowledge for public benefit

Recently, increasing calls for universities to do item 3.

§8 Day Science and Night Science

Einstein used to say, "If you want to know how scientists operate, don't listen to what they say but rather look at what they do." We should recognize that science also has dual characteristics. One side is logical, objective, cold and rational, or rigorous - the side of the perfect product, as presented in text books. It is by tradition that this is the side exposed to the public at meetings and conferences. I am quite sure that what Einstein meant was that listening only to reports on completed projects is not a useful way to gain an understand of the true nature of science.

The other side of science is imaginative, subjective, individualistic, intuitive and lively, involving the process whereby something new is created. This process relies on perception and inspiration, of course, with a base in sharp intellect. Scientists may use their imagination to search blindly in a desperate struggle of trial and error for the key to some of the underlying secrets of the universe. If by chance a solution emerges, as it sometimes does, and all their effort is rewarded, they really rejoice. This is what Einstein meant when he said, "Look at what they do."

We could use the term "day science" for the logical side, and "night science" for the imaginative side. Of course, both sides complement each other and both are needed for progress. But, the embryo of discovery or of a new theory is always found in the "night science."

§9 How to Win a Nobel Prize — Five Don’ts

In closing, I would like to offer a list of five “don’ts” which anyone with an interest in realizing his or her creative potential should follow. Who knows, it may even help you win a Nobel Prize.

Rule number one: Don’t allow yourself to be trapped by the constraints of your past experience. If you allow yourself to get caught up in social conventions or circumstances or preconceived ideas, you will not notice the opportunity for a dramatic leap forward when it presents itself. Looking back at the history of the Nobel Prize, you will notice that most of the laureates in the sciences have received the Nobel Prize for work they undertook in their thirties. In my case I was 32 years old when I developed the "Esaki tunnel diode." The point that I am trying to make is that younger people are able to look at things with a clearer vision, one that is not clouded by social conventions and past history.

Rule number two: Don't allow yourself to become overly attached to any authority in your field the great professor, perhaps. By becoming too closely involved with the great professor, you risk losing sight of your own self and forfeiting the free spirit of youth. Although the great professor may be awarded the Nobel Prize, it is unlikely that his subordinates will ever receive it.

Rule number three: Don't hold on to what you don't actually need. The information-oriented society facilitates easy access to an enormous amount of information. Be careful of misinformation and badly organized information. The brain can be compared to a personal computer with an energy consumption of about 25 watts. In terms of memory capacity or computing speed, the human brain has not really changed much since ancient times. Therefore, we must constantly be inputting and deleting information, and we should save only the information that is truly vital and in a relevant form. As the president of a university, I have the opportunity to meet with many people and to exchange 'meishi' (name cards) with them. I try to discard the name cards as soon as possible, so that I always leave maximum memory space open. I'm kidding, of course...

Rule number four: Don't avoid confrontation. I myself became embroiled in some trouble with the company I was working for many years ago. At times, it is necessary to put yourself first and defend your own position. My point is that fighting in self-defense is sometimes unavoidable.

Rule number five: Don't forget your spirit of childhood curiosity. It is a vital component for imagination.

Having listed these five rules, let me say that they do not constitute the sufficient conditions for success. They are merely suggested as guidelines. So good luck!