ASM Lecture Series

Science and Technology in the Twenty-First Century

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INTRODUCTION

Assalamualaikum w.r.t.,
Ladies and Gentlemen

The title of my lecture implies that I will make predictions about science and technology (S & T) in the twenty-first century, but I know better – one should be cautious about making predictions as many in the past have proven to be off the mark. Take, for example, the prediction made in 1943 about the future of the computer by Thomas J. Watson, founder of IBM: "I think there is a world market for about five computers." In retrospect, this is a remarkable statement given that today we have billions of computers!

It is in the nature of science that we scientists search for the truth in the unknown, which is so vast and complex that our predictions will always be constrained by our ignorance of the future. The renowned historian of science Karl Popper described the state of knowledge this way: "Our knowledge can only be finite, while our ignorance must necessarily be infinite." The famous actor Woody Allen cast the same sentiment in a more humorous light: "Can we actually 'know' the universe? My God, it's hard enough finding your way around in Chinatown." Indeed, it is hard to predict the future, but it is hoped that with insight we can ask the right questions, gain new knowledge, and develop new technologies. In this process of scientific research it is essential that we understand the culture of science and its foundations – inherent continuity, uncertainty, and unmanageability.

SCIENCE AND ITS METHODOLOGY

Since the beginning of human civilization, science and technology has progressed in a continuous process. Fire must have been an exciting new technology for the first humans and to this day we are continuing research to fully answer the question, what is fire? But the search for new knowledge is based on *rational thinking*, which is fundamental for progress and for making new discoveries. I doubt whether there was (or now is) a civilization that reached a high level of achievement without simultaneously nurturing S & T and employing the rational thinking characteristic of the culture of science. After all, we are *Homo sapiens*, the species characterized by an enlarged brain capacity.

Science is an education process that allows the educated and creative minds to question, experiment or observe in an attempt to find answers, and then try to identify a set of unifying principles, concepts, and laws that embraces all phenomena of nature. The aim is to better understand our universe and gain new knowledge that will enlighten humanity by unveiling mysteries of how nature works. In the process we may make new discoveries and inventions that change the way we think and/or create new technologies that transform our society.

The sharp division of science into pure and applied branches is not natural. Some managers of science believe in this division and wish to emphasize only "what is relevant" for the prosperity of the society. But that is not the way science works, as scientists themselves in their quest for new knowledge do not know what is relevant. And if they knew ahead of time it would not be new knowledge. Scientific research is not manageable in the usual sense of the word.

THE TRIAD – THE CLONING CASE

Most S & T advances are governed by a structure of a connected triad – basic research, technology development, and the involvement of society. In this cycle, both pure and applied science become an integral part of a successful endeavor. Take the case of cloning, a current subject of significant relevance to the definition of *species*. Cloning began as a laboratory experiment on the genetic material of our cells, DNA. But these experimental achievements would not have been possible without scientific research and advances over a half century of development in many areas: the discovery of the genetic code, molecular structure of DNA, recombinant DNA, and other related studies. Moreover, a century of development of new techniques and tools provided the means: x-ray crystallography, polymerase chain reaction (PCR), genetic engineering, as well as computer data processing.

Then came the first successful cloning of a higher organism – Dolly, the sheep – an act that transformed laboratory research into an enterprise with possible benefits to human medicine. But the third element of the triad, the society, must now be involved to develop a full perspective of the moral, ethical, and religious implications of cloning. With rational thinking, the benefits of cloning and other developments, such as stem cell research, to society will undoubtedly feed back to the support of basic research, and the cycle of the triad continues.

REVOLUTIONARY PARADIGMS

Cycles of this type ultimately lead to the development of new concepts and new tools or techniques. Some historians of science make a division between the two. The late influential historian and philosopher of science, Thomas Kuhn, favored *concept-driven* research as a paradigm over *tool-driven* research. Although I am not a historian, I find, from my own experience as a scientist, this distinction is not as sharp as Kuhn would have it. In fact, new tools and techniques drive scientific research as much as new concepts, and both are part of the progress of science.

Gravity, relativity, and quantum mechanics are concepts that surely have changed the way we think. With these concepts we can describe phenomena of nature and understand their fundamentals – objects attract each other depending on their masses and the distance between them (gravity); objects that are massive or move at very high speed do not follow Newton's classical laws of mechanics (relativity), and objects of microscopic size also do not follow the laws of Newton (quantum mechanics). But these concepts and rules need to be tested experimentally and the phenomena have to be observed and studied. Moreover, in most cases the concepts and rules develop as a result of experimentation and observations that are made possible with new tools and techniques. In fact, one may argue that techniques for experimentation and observation are prerequisite for the development of concepts. Of course, these techniques must be used creatively in order to develop new paradigms and concepts.

CAMERA OBSCURA, MICROSCOPE, AND TELESCOPE

The microscope, the telescope and the simple *camera obscura* were revolutionary not only because they made it possible to observe the very small and the very far, and to record a picture of what is viewed, but also because they changed the way we think of biology, astronomy, and vision. The conceptual pioneer of *camera obscura* was ibn al-Haytham (known in the West as Alhazen; ca. 965–1038), a Muslim polymath acknowledged to be the greatest scientist of the European Middle Ages. The principle of *camera obscura* (among other observations) explained at the time the nature of light – it travels in straight lines, it has high speed, and it reflects from bodies (and refracts in media) into the 'human camera', the eye. Alhazen's work in optics caused a paradigm shift about vision – a reflection of light from objects to the eyes instead of radiating light from them – and established the foundation for the new technologies of still and motion picture photography.

The light microscope was developed in the middle of the seventeenth century. In Holland, Antoni van Leeuwenhoek (1632–1723) and in England Robert Hooke (1635–1703) made astounding discoveries, including observation of tiny moving creatures in droplets of water, sperms, and the cellular structure of slices of cork. Hooke coined the word *cell*, and his greatest work, *Micrographia* (1665), defined microscopy as a scientific discipline. As a result of these advances, the history of biology has shifted from an emphasis on classifying living organisms and plants to studying the living cells – the exploitation of new tools produced cell biology as a new branch of science. Molecular biology and genetics are the most recent frontiers reached with the aid of other developments based on the use of electromagnetic waves, those of x-ray diffraction by DNA and protein crystals and nuclear magnetic resonance (NMR) of macromolecules. Through scientific experimentation the microscope has magnified the world of the very small – microns in size – so it is visible to our eyes. As a result human medicine has changed forever.

The telescope was invented before the microscope, in the early part of the seventeenth century; some believe that the first optical assembly of this nature was made in 1550. Hans Lippershey, an eyeglass maker based in Holland had developed telescopes (1608-09) with a magnifying power of about three times. These and later telescopes were made from a combination of concave and convex lenses and the effect produced was understood from studies of the refraction and reflection of light (e.g., those by Alhazen and later by the Dutch scientist Willebrord Snell). Galileo Galilei (1564–1642) was the first to make use of the telescope to visually approach the very far, first of ships and then the heavens. Through scientific observations (1610) of Jupiter's moons, which revolve around a planet other than Earth, Galileo refuted the long-held dogma of geocentrism, proving that the stationary Earth is not at the center of the universe with the planets and sun revolving around it. The geocentric model – Ptolemaic astronomy at the heart of Aristotelian world view – was to be replaced by the heliocentric model of Copernicus (1473–1543), in which the sun is the fixed center of the universe and the planets, including Earth, are in circular orbits around the sun; Kepler (1571–1630) refined the Copernican model by showing that astronomical bodies follow elliptical orbits in their motion. Without these techniques and concepts we could not launch a spaceship or a satellite or hope to understand our universe.

FEMTOSCOPE AND MATTER'S ULTRAFAST UNIVERSE

Resolution of time is not a property of the microscope or the telescope, and to study ephemeral phenomena of matter we needed new developments. At Caltech, the integration of new techniques and concepts led to the development of the "femtoscope", which brings to vision the motion of atoms in real time. In so doing we are able to uncover the underlying fundamentals of the dynamics in simple and complex systems, and examine the forces responsible for the diverse molecular functions in diseases such as cancer, in the sense of taste, and in the elementary mechanism for food digestion.

In the microscopic world – the quantum world – the motion of atoms can be observed only with an 'artificial eye' having a speed one million million times faster than our naked eye, which responds in a fraction of a second. Microscopic motion is ephemeral and ultrashort in duration, and we need a telescope that not only brings their very far world up close for observation, but also freezes them in time so we can take snapshots. Ultrafast laser optics is the essential element of this "femtosecond telescope", the femtoscope. A femtosecond is 10^{-15} second or 0.000 000 000 000 001 second. In one second, light travels about 300,000 kilometers, almost from Earth to the moon; in one femtosecond, light travels 300 nanometers (0.000 000 3 meter), the dimension of a bacterium, or a small fraction of the thickness of a human hair.

In principle, with femtosecond timing, the atom's motion becomes visible, but how can we advance stop-motion photography to reach the scale of the atom? In the nineteenth century, the motion of animals was recorded for the first time using light shutters and flashes. In Paris, Étienne-Jules Marey, a professor at the Collège de France, was working (1894) on a solution to the problem of action photography: chronophotography, a reference to the regular timing of a sequence of images. Marey's idea was to use a single camera and a rotating slotted-disk shutter, with exposures on a single film plate or strip that was similar to modern motion picture photography. Marey was interested in investigations of humans and animals in motion, including a subject that had puzzled people for many years, namely the righting of a cat as it falls so that it lands on its feet. Marey's work and that of Eadweard Muybridge on the horse have changed the way we think of the behavior of animals (and humans) in motion.

For the world of atoms in molecules, if the above ideas of stop-motion photography can be carried over in a straightforward manner, then the requirements can be identified for experiments in femtochemistry – the field of studying molecular motions on the femtosecond time scale. For a molecular structure in which atomic motions of a few angstroms (an angstrom, Å, is 10^{-8} cm) typically characterize chemical reactions, a detailed mapping of the reaction process will require a spatial resolution of less than 1 Å (about 0.1 Å). Therefore, the shutter time, or time resolution, required to observe with high definition the molecular transformations in which atoms move at speeds of the order of one kilometer per second (1000 m/s) is 0.1 Å divided by 1000 m/s, which equals 10^{-14} second or 10 femtoseconds – a million million times shorter than what was needed for Marey's (or Muybridge's) stop-motion photography.

However, such minute times and distances mean that molecular-scale phenomena should be governed by the principles, or language, of quantum mechanics, which are quite different from the familiar laws of Newton's mechanics that were used in the description of the motion of the cat and horse. Conceptually and experimentally we addressed these issues, and in 1987 we reached our goal of observing in motion, for the first time, Democritus' atom – theorized by the Greek philosopher some 2500 years ago – and we could describe it on the femtosecond scale as a classical object like the cat and horse. The similarity between atomic motions and planetary classical motions brings about an analogy between the femtoscope and the telescope. In reaching the femtosecond domain of the atom, with a scale of a millionth of a billionth of a second, the time resolution of today compared to that of a century ago, with a scale of a thousandth of a second, is like one day compared to the age of the universe.

With the femtoscope, the breadth of applications emerging from all over the world spans very small to very complex molecular assemblies and all phases of matter. An example that demonstrates the unity of concepts from small to large molecular systems came from a paradigmatic study case made at Caltech on a sibling of the table salt (two atoms) and at Berkeley on the protein molecule of vision (hundreds of atoms). In both, the primary step involves femtosecond motion of the atoms, and we now understand better the remarkable coherent and highly efficient first step of vision at the atomic level.

An especially exciting frontier for femtoscience is in biology. At Caltech we now have the National Science Foundation's Laboratory for Molecular Sciences (LMS) for interdisciplinary research on very complex systems. Among the recent new studies published are those concerned with the conduction of electrons in the genetic material, the binding of oxygen to models of hemoglobin, molecular recognition of protein by drugs, and the molecular basis for the cytotoxicity of anticancer drugs and of digestion. We are also developing new techniques to observe the behavior and architecture of these complex molecules – in space and time – using diffraction images, which gives the 3-D location of all the atoms, all at once! The impact on biology and medicine is clear.

As for technology developments – femtotechnology – there are exciting new developments in microelectronics (femtomachining), femtodentistry, and femtoimaging of cells and tumors, not to mention possible new developments with intensities reaching that of the sun (in femtoseconds!) and duration going beyond the femtosecond (attosecond), and the interface with nanoscience and technology – marrying time and length scales. The ability to count optical oscillations of more than 10^{15} cycles per second will lead to the construction of all-optical atomic clocks, which are expected to outperform today's state-of-the-art cesium clocks, with a new precision limit in metrology. There is also the potential for using powers reaching 10^{20} watts/cm^2 to induce nuclear fusion in clusters of atoms through Coulomb explosion. And, the possibility of controlling matter on the femtosecond time scale – one day we may direct chemical reactions into specific or new products. None of these developments, applications, and technologies were strategically planned and managed.

FUTURE FRONTIERS

With these reflections on the culture and progress of science, what do I expect for S & T in the twenty-first century? I see three major frontiers that through the triad of basic research, technology development, and the involvement of society will be rich in new paradigms and have direct impact on human life.

Our matter – the scale of the very small. We are on our way to being able to manipulate matter at its smallest, most fundamental limits, both in time, on the femtosecond scale, and in length, on the nanoscale. Just think about these new scales of time and space in the world of the very small. If your heart beats once a second, now we can see the beats of atoms in a femtosecond, in a millionth of a billionth of a second – a femtosecond is to a minute as a minute is to the age of the universe. Similarly, we can study matter on the nanometer scale and resolve the atoms in their structures – the size of the atom to the size of the earth is like the size of the earth to the whole universe. The opportunity is huge for acquiring new knowledge and for creating new forms of "our matter." The manipulation of matter to produce new sources of energy (photovoltaic/photosynthetic, etc.) should become a major undertaking. The interface of matter's micro- and nanonetworks, designed to produce artificial intelligence, to our life organs, such as the brain, will be another frontier that could alter the boundaries and meaning of species.

Our universe – the scale of the very big. In this century, we may have colonies on the moon, and we may have our second homes on other planets and maybe even in other solar systems. Just think of the scales of the world of the very big. Our universe is about 12 billion years old, and at the speed of light (300,000 km/s), our universe's limit of distance is 100 billion trillion kilometers – certainly enough space for the six billion people on earth today, even multiplying by ten or by one million for the future! The opportunities involving outer space and information technology are unlimited. On our planet, through 'virtual walls', which in principle will provide any information one needs, education and intelligence in all societies will be redefined.

Our life – the scale in between. In the first year of this century, the sequencing of the human genome was completed. We now have the genetic map that describes every human on planet Earth. Just think, three billion letters have been deciphered and read into our book of life. The history of biology has changed from the classification of living organisms (Darwin's theory), to the world of cells (Leeuwenhoek–Hooke microscope), to now the molecular world (Watson and Crick's DNA) with revolutionary ideas in genetic engineering. Soon we might see a nanoscale motor entering the cell to do work. Medicine and human health will certainly enter a new age.

CAUTIONARY REMARKS

The scope of opportunities is wide ranging and the promise in these new and other areas of science for new discoveries and new technological developments are becoming a reality. But I have a few cautionary general remarks to make.

First, in the new mode of research in the twenty-first century, we should not become professional technical experts in narrow areas of specialization. In this regard, multidisciplinary science may help, but should not be at the expense of depth and scholarship.

Second, the mix of science and business by scientists is a concern that in this century may, in my opinion, have a detrimental impact on the culture of science and commitment to scholarship. Academia should remain the place for free exchange, motivated primarily by the search for new knowledge and education of students.

Third, the support of research should be granted for the best ideas and the best people, not for strategic- or mission-oriented, and managed, research. James B. Conant, the renowned educator and scientist and former President of Harvard University, in a 1945 letter to The New York Times commented: "There is only one proven method of assisting the advancement of pure science – that of picking men [and women] of genius, backing them heavily, and leaving them to direct themselves." Naturally, there should be other places for carrying out research and development for specific national missions, but institutes of knowledge should not be managed and missioned. Investment in science and education is the best thing a nation can do for posterity.

THE WORLD OF THE HAVE-NOTS

For the developing nations, there are barriers for progress, but I see no way out of investing in science education and science development. A look at global S & T is illuminating. The total number of scientific papers published worldwide over the past five years is 3.5 million. The European Union's share is 37%; the United States, 34%; Asia Pacific nations, 21%. The United States contributes 30% to 40% to the world economy and the strong correlation between the advanced state of S & T and the advanced state of the nation is clear. Asian Pacific countries are showing exponential growth in S & T papers and this too explains their increased position in the world economy. Other correlations of gross domestic product (GDP), health status, life expectancy, and illiteracy show the critical role of science education and scientific research in the global positioning of nations.

The lack of a solid science and technology base is not always a result of poor capital or human resources. It sometimes stems from a lack of appreciation of the critical role of S & T in development, an incoherent methodology for establishing such a base, and an absence of a coherent policy addressing national needs, and human and capital resources. Some countries consider scientific progress to be a luxury, as measured against other demanding concerns. Others believe that the base can be built by buying technology from developed countries. These beliefs translate into poor or, at most, modest advances that are based on the efforts of individuals, not institutional teamwork.

These issues point to three essential ingredients for progress. First is the building of human resources by eliminating illiteracy, ensuring active participation of women in society, and reforming education. Second is to rethink national constitutions, allowing for freedom of thought, minimizing bureaucracy, developing a merit system, and creating a credible – and enforceable – legal code. Third is the building of a science base.

The foundations of a science base are investment in special education for the gifted, the establishment of centers of excellence, and the chance to apply knowledge in the industrial and economic markets of the country and, eventually, the world. This must go hand-in-hand with a plan for general education at state schools and universities. With such a vision, a scientific culture will emerge that enhances a country's ability to follow and discuss complex problems, rationally and collectively. Scientific thinking becomes essential to the fabric of the society.

Developing countries need centers of excellence, not only for research and development, but also for training experts in advancing technologies and so reducing the brain drain experienced by many such countries. It is important that these centers are not just exercises in public relations: They should be limited to a few areas of research in order to build confidence and recognition. In the coming fifty years, knowledge-based and skill-based societies will have the lion's share of the world market and high status. Without S & T how can the have-nots participate in current world issues such as stem-cell research, cloning, human genome sequencing, artificial intelligence, manipulation of matter, molecular medicine, and cosmology? Without S & T how can they actively contribute to the world market in technologies such as microelectronics, information and communication, new materials, and the revolutionary biotechnologies?

The challenges require a new system of education and a new outlook on technologies. Technologies fall into three categories, those that are 'simple' but relevant to services, solving domestic problems of everyday life, from traffic lights to desalination of water; those that are 'innovative', which make participation in the world market possible, such as microelectronics; and those that are 'frontier', which are concerned with research into the unknown, representing an investment in the future. To be effective, a new system of education and research and development in the first two categories are required and, at the least, there must be serious engagement with the issues of the third, frontier category – where the world is going to be. Developing countries must address these issues with a new action plan and serious commitment.

But it is also the responsibility of developed countries to focus aid programs. Usually an aid package is distributed across many projects, with a lack of follow-up that leads to a diffusion of resources and in some cases corruption, so the aid does not result in significant successes. Real focus can be achieved by establishing what I call "partnership-guided aid", with a major portion of the aid being directed toward excellence using criteria established in developed countries.

There must also be a minimization of politics in aid. The use of an aid program to help specific regimes or groups is a big mistake, as history has shown that it is in the best interests of the developed world to help the the people of developing countries. Aid programs should be visionary in their mission and supportive of investment in future developments. Developed nations either can give money as charity write-offs or they can become partners, providing expertise and a follow-up plan.

EPILOGUE

Let me end on a hopeful note. If humanity's quest is progress and prosperity, we will need to weave the rational scientific approach, which is basic to our definition as *Homo sapiens*, into the fabric of our civilizations; if we do so, I can predict a bright future. Surely, science and technology will then become the real spaceship for the successful voyage of posterity.