BIBLIOTHECA ALEXANDRINA
مكتبة الإسكندرية

TIME'S MYSTERIES AND MIRACLES

Consonance with Physical and Life Sciences

Lecture delivered by Ahmed Zewail during BioVision Alexandria,

Nobel Laureates Day, at the Bibliotheca Alexandrina, on 3 April 2004

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INTRODUCTION

An Amazing Legacy

The very name of the Bibliotheca Alexandrina conjures up the image of a glorious past, of a shared heritage for all of humanity. For it was indeed at the Ancient Library of Alexandria that the greatest adventure of the human intellect was to unfold. Launched in 288 BCE by Ptolemy I (Soter) under the guidance of Demetrius of Phaleron, the temple to the muses, or Mouseion (in Greek), or *Museum* (in Latin) was part academy, part research center, and part library. The great thinkers of the age, scientists, mathematicians, poets from all civilizations came to study and exchange ideas.

They and many others were all members of that amazing community of scholars, which mapped the heavens, organized the calendar, established the foundations of science and pushed the boundaries of our knowledge. They opened up the cultures of the world, established a true dialogue of civilizations. For over six centuries the ancient Library of Alexandria epitomized the zenith of learning. The library completely disappeared over 1600 years ago…but it continues to inspire scientists and scholars everywhere. To this day, it symbolizes the noblest aspirations of the human mind, global ecumenism, and the greatest achievements of the intellect.

The Rebirth of the Bibliotheca Alexandrina

Sixteen-hundred years later, under the auspices of President Mohamed Hosni Mubarak, and with the continuous untiring support of Mrs. Suzanne Mubarak, it comes to life again. The Bibliotheca Alexandrina, the new Library of Alexandria, is dedicated to recapture the spirit of the original. It aspires to be:

- The World's window on Egypt;
- Egypt's window on the world;
- A leading institution of the digital age; and, above all
- A center for learning, tolerance, dialogue and understanding.

To fulfill that role, the new complex is much more than a library. It contains:

- A library that can hold millions of books;
- A center for the Internet and its archive;
- Six specialized libraries for (i) audio-visual materials, (ii) the blind and visually impaired, (iii) children, (iv) the young, (v) microforms, and (vi) rare books and special collections;
- Three Museums for (i) antiquities, (ii) manuscripts, and (iii) the history of science;
- A Planetarium;
- An Exploratorium for children's exposure to science;
- Three permanent exhibitions;
- Six art galleries for temporary exhibitions;
- A Conference Center for thousands of persons;
- Seven research institutes covering (i) manuscripts, (ii) documentation of heritage, (iii) calligraphy and writing, (iv) information sciences, (v) Mediterranean and Alexandrian Studies, (vi) arts, and (vii) scientific research; and
- A forum for dialogue and discussion.

Today, this vast complex is a reality, receiving more than 870,000 visitors a year, and holding hundreds of cultural events every year.

The Academia Bibliotheca Alexandrinae (ABA)

The greatness of the Ancient Library resided as much in the remarkable community of scholars that it had helped create as in the vast collection of manuscripts it assembled. They represented the best in the World of their time.

Today, to recapture the spirit of the ancient Museum, we have established the Academia Bibliotheca Alexandrinae (ABA), to include 100 of the greatest minds of the contemporary world. Today, with the magic of the Information and Communication evolution, these eminent men and women can and do reside and work in all parts of the world. The ABA is a "virtual organization" with a small secretariat established at the Bibliotheca Alexandrina in Alexandria, Egypt. The Director of the BA functions as the secretary to the ABA.

The ABA will create and maintain an international network of scientists, artists and scholars dedicated to:

- The promotion of excellence in science and the arts;
- Helping build international goodwill, primarily through collaborations between scientists, scholars and artists;
- Spreading the values of science, and the culture of science in Egypt and the region;
- Fostering openness to the other, through inter-cultural dialogue; and
- Encouraging tolerance, rationality and dialogue.

Beyond the virtual network, a special event of the ABA shall be organized tri-annually. Between the proposed meetings every three years, many activities sponsored by the ABA will take place. Indeed, individual members come and visit the New Library at different times and they and their guests, deliver lectures here.

The Distinguished Lecture Series

In the spirit of spreading the goals and values that the ABA espouses, and the Bibliotheca Alexandrina's commitment to its mission, it was considered appropriate that the Distinguished Lecture Series should be developed to record and make available in an affordable format some of the distinguished lectures delivered at the BA by members of the Academy or their distinguished guests. Thus was the Distinguished Lecture Series born.

There is no specific frequency for the issuing of these publications of the occasional lectures. We would expect no less than three such published lectures to appear every year, and sometimes there will be substantially more. The series is driven by content and quality, not by timing.

In terms of coverage, the scope of the ancient library or the modern BA and its Academy (the ABA), the Distinguished Lecture Series includes science, the arts, politics, and every aspect of the human condition. The only requirement is the rigor of the presentation and the distinction of the lecturer. It is as broad as the human imagination, as varied as the fields of knowledge whose mosaic creates the universal human experience, and as engaging as the talents of the distinguished speakers who bring to life the different topics of their choice. Each lecture stands on its own. It can be appreciated as an experience in its own right. It does not have to be read in relation to any of the others.

It is our hope that by publishing this series, the Bibliotheca Alexandrina is allowing many more individuals to share the lectures than those who have attended the actual event. It safeguards the material for posterity and invites those who are so inclined to view the actual video record of the lecture, which is safeguarded in the Library's multi-media section.

To make the publication more suited for the reader, a special introduction has been included which explains the work of the individual concerned and positions the lecture in relation to that body of work. Each publication also includes a bibliography of selected works and a short biography of the lecturer.

Ismail Serageldin
Librarian of Alexandria
Director of the Bibliotheca Alexandrina
Secretary of the Academia Bibliotheca Alexandrinae

FOREWORD

The first Nobel Prize-winner in science from an Arab country, Dr. Ahmed H. Zewail is at the forefront of his field winning the 1999 Nobel Prize in Chemistry and establishing the whole new realm of femtochemistry. He is the Linus Pauling Chair Professor of Chemistry and Professor of Physics, and heads the NSF Laboratory for Molecular Sciences at the California Institute of Technology.

Dr Zewail was born in 1946 in Damanhour, Egypt, 60 km south of Alexandria, where he showed early promise in his science classes; his family even jokingly put the sign "Dr. Ahmed" on his door. Dr. Zewail received his BSc and MS degrees from the University of Alexandria, where he was a brilliant student, giving "professorial lectures" at age 21. His advisors at the university recommended he do further training in the US, and against enormous odds (the 1967 war had just ended), he obtained a scholarship to University of

Pennsylvania, from which he received his PhD. Upon completion of his doctorate, he went to the University of California at Berkeley as an IBM research fellow. In 1976, he accepted a position as assistant professor of chemical physics. Full professorship and tenure soon followed, and in 1990, he became the first Linus Pauling Chair at Caltech.

Much of the scientific endeavor of the 20th century was involved with the nature of time and the behavior of the smallest particles of matter. Einstein's theory of relativity ushered in a new era in physics, irrevocably linking time, matter, and energy, and subsequent research has attempted to close in on the actions of the tiniest particles in the smallest time-frames. Dr. Zewail's area of research, femtochemistry, is concerned with incredibly small fractions of a second, the femtosecond (10^{-15} of a second), and the problems of recording molecular and atomic movement at such minute time intervals. To explain just how small a femtosecond is, consider that from a femtosecond to one second is the same as from one second to 32 million years! Who can comprehend or even imagine 32 million years? Our history barely reaches seven to eight thousand years before receding into the mists of the very distant past. Yet that is the scale of the achievement of Dr. Zewail, experimentally, not just through the manipulation of abstract mathematical formulae.

Already at the University of Alexandria, Dr. Zewail had become interested in spectroscopy, an interest he pursued at the University of Pennsylvania, with special focus on molecular pairs. At Berkeley, he continued to investigate spectroscopy, this time with highly refined tools at his disposal. He worked with Dr. Charles Harris on making a picosecond laser (2 picosecond is 10^{-12} of a second, one-thousand times longer than 2 femtosecond). This experience served him well in later experiments using laser technology to "photograph" chemical reactions at femtosecond intervals. His findings are at the cusp of present research in physics and chemistry, and have had enormous influence in the scientific world. For his groundbreaking work in femtochemistry, he received the Nobel Prize in Chemistry in 1999. In the citation, the Nobel Prize Committee said: “This year’s laureate in Chemistry is being rewarded for his pioneering investigation of fundamental chemical reactions, using ultra-short laser flashes, on the time scale on which the reactions actually occur. Professor Zewail’s contributions have brought about a revolution in chemistry and adjacent sciences, since this type of investigation allows us to understand and predict important reactions.”

Dr. Zewail’s work has had a profound impact on chemistry and biology around the world. Experiments using the femtosecond techniques he pioneered are being used to examine processes on surfaces, to help improve catalysts; in liquids, where they help clarify the mechanics of reacting substances in solution; and in polymers, where they are being used to create new materials for use in electronics. In biology, the use of femtosecond lasers has demonstrated the ultra-fast beginnings of reactions, leading to new insights into the function of the retina and the uptake of oxygen into the blood. Many scientists predict that microbiology will be to the 21st century what physics was to the 20th, and if this is proven correct, Dr. Zewail's work will be viewed as a cornerstone of this new paradigm.

Dr. Zewail is also known for his lectures and his lucid explanations of complex physical and chemical processes. In this lecture, he begins with an overview of physics in the first decades of the 20th century, with particular attention paid to the nature of time. He then discusses the history of photographing moving objects, from the first crude attempts by Eadweard Muybridge through the more refined efforts of Étienne-Jules Marey, and then into the difficulties involved in making images at femtosecond intervals.

A major hurdle, and one which had led many sceptics to doubt that photography at femtosecond level was possible, was Heisenberg's uncertainty principle, which asserts that one cannot measure both the position and momentum of a particle at the same time. Dr. Zewail explains, in his characteristically straightforward manner, how this difficulty was overcome. Though one deals at molecular level with probabilities, these probabilities become wavefunctions which may be organized so the probability distribution is localized, acquiring the characteristics of a particle. It then becomes possible to make an image of the motion of the "particle".

Dr. Zewail then moves into a discussion of the uses of laser photography at femtosecond intervals to "see" chemical processes. At present, a new methodology, termed utrafast electron crystallography, is being used to examine the role of water in biological systems. The interaction of water molecules with proteins and DNA is of paramount importance in biology, and will have a profound impact on medicine. Dr. Zewail concludes by discussing some of the recent developments in femtotechnology, including the possible creation of extremely precise clocks and the possibility to induce nuclear fusion using techniques he developed.

The Ancient Library of Alexandria was at the forefront of the search for scientific knowledge. Here Eratosthenes, Hipparchus, and Euclid made lasting contributions to humanity. It is appropriate that a child of this region, who did his initial studies at the University of Alexandria, and whose work, like theirs, will continue to influence the global scientific community for a long time, should be our honored guest at the Bibliotheca Alexandrina for this outstanding lecture. Furthermore, we are delighted that he has been one of the founding members of the Board of Trustees of the Bibliotheca Alexandrina, guiding its initial steps.

Along with his scientific research, Dr. Zewail is noted for his humanitarian work. He makes it a point to communicate his knowledge through lectures, and has been instrumental in trying to bring a higher standard of education to the developing world. One of the stated aims of the Academia Bibliotheca Alexandrinae is to spread the values and culture of science in Egypt and the region, and it is a pleasure and an honor to welcome a true Alexandrian ambassador for science back to a city he once called home.

TIME'S MYSTERIES AND MIRACLES
Consonance with Physical and Life Sciences*

Introduction

Ever since the dawn of history, humans have been the benefactors of time's miracles, but at the same time they have been baffled by time's mysteries. More than six millennia ago, the philosophy and measurement of time occupied the minds of scholars in the land of Bibliotheca Alexandrina, and, even today we struggle with the meaning of time. In this overview, I present some concepts and techniques developed in the science and technology of time, and an exposé of some of the

*Based on the Albert Einstein public lecture delivered in New Delhi, and adapted for the BioVision Nobel Laureates Day.

mysteries and miracles that are in harmony with physical and life sciences.

Einstein spent a great deal of time thinking about time. In his theory of relativity, time is relative; its passage depends on how fast we travel relative to the speed at which light travels (300,000 km per second). In principle, time can be dilated and even stopped. Shakespeare knew this. His words were philosophic when he said "And time that takes survey of all the world must have a stop."

Perhaps the most puzzling issues, which have been with mankind for millennia, can be expressed in three questions: What is time? Why does it have a direction? How can it be resolved? The most complex question of all is the first one, because we really do not know what time is, and this leaves us with gray areas in the science and philosophy of time. One definition was given by C.J. Overbeck: *"Time is the great gift of nature which keeps everything from happening at once."* Independent of its definition, we know that our perception of time depends on its duration, scale, and universality.

From the Microscopic to the Cosmic

All phenomena that we know of in our universe are defined by their time scales. Enduring or ephemeral in their character, these phenomena seem to follow an intriguing logarithmic scale of time that spans the very small (microscopic) world and the very big (cosmic) world. The human time-scale lies almost in between, a geometric average of the two extremes (Figure 1).

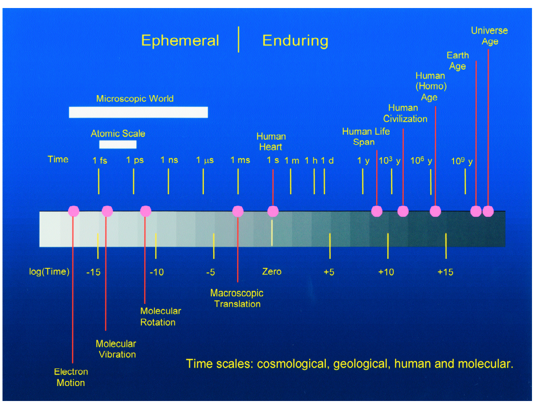

Figure 1. Time scales in cosmological, geological, human and molecular events.

The time of the big bang, the age of the universe, is about 12 billion years, or tens of 10^{+15} second (+15 on the log scale), recalling that one year is 32 million seconds. For the lightest atom, hydrogen, the time scale for the motion of an electron in its first orbit is about a tenth of a femtosecond, or a tenth of 10^{-15} second (-15 on the log scale). The average of the two limits is on the scale of seconds (zero on the log scale), the human heart beat–something to think about!

On this log scale, we did not consider the ultimate–shortest–time of the universe, what is now known as Planck's time. In his attempt to give a universality to constants of nature, Planck in 1899 proposed that natural units of mass, length, time, and temperature can be constructed from the most fundamental constants: the gravitation constant G, the speed of light c, and the constant of action h (which now bears his name). By dimensional analysis, the shortest possible time becomes:

$$t(Planck) = (h\,G/c^{5})^{1/2}$$

which is 10^{-43} seconds, and the corresponding length is 10^{-33} cm, obtained simply by multiplying by *c*. Even before 1900, the year quantum mechanics began to emerge, this unity in defining Planck's time is telling of "relationships" between quantum mechanics (*h*), gravity (*G*), and relativity (*c*). Implicit in this unification is the meaning of physical laws at scales below these values, and the nature spacetime with a universal speed of light – Einstein enters here!

Time, Light, and Relativity

Before Einstein, the great contribution by James Clerk Maxwell gave us a universal description of the nature of light. By a unification of electricity and magnetism, light, as a wave, propagates in space and time with electric and magnetic (electromagnetic) disturbances. This was a brilliant contribution expressed quantitatively in Maxwell's equations. Einstein in 1905 was concerned about two issues that relate to the nature of light–Is it really a wave? and, What happens to these waves if you can imagine running with them near the speed *c*? The first issue is not our concern here, but the second one is.

Something is special. Whichever direction a beam of light is coming from, independent of our own velocity for observation on Earth, we will always measure *c* for light. Einstein, in his special theory of relativity, gave the correct picture for adding velocities: For a motion of an object (say a moving ball) with velocity v in a reference frame (say a moving train) with a velocity *u*, an observer will see a motion not by the expected v + *u* velocity, but by v + *u* divided by the factor $(1+\mathrm{v}u/c^2)$; when the speeds v and *u* are the "normal" ones, that is, much less than c, then the total velocity is the expected (Newtonian) v + *u*. However, if instead of the ball we have light with speed *c*, then the total velocity becomes *c* + *u* divided by $(1 + u/c)$ which is exactly *c*. The speed of light is the same in all reference frames, in all directions, for all observers, and every observer will experience the same natural laws.

The consequences of these findings for time, length, and mass require some philosophical interpretation. As the speed of light is approached, the length of a spaceship will shrink and approach zero in the direction of the motion. Similarly, moving objects become more massive and approach infinity when the object velocity becomes near the speed of light. For time, the mystery continues. Moving clocks must slow down and stop when the object velocity reaches the speed of light. In this "Dilation of Time," time becomes relative:

$$t(\text{moving}) = t(\text{stationary}) / (1-\mathrm{v}^2/c^2)^{1/2}$$

where the velocity of the moving clock is v. From the expression, we note that the time of the moving clock gets longer (slowing down) as v increases, but we also note that if v is made to exceed c, we enter an imaginary world of time! Thus, within the framework of this theory, the speed of light is the ultimate speed in our world and universe.

In approaching these large scales of speed and mass, what happens to light? In his 1911-16 papers on the

General Theory of Relativity, Einstein addressed the effect of gravity on light. Gravity is described as distortions in the four dimensions of space and time (three dimensions for space and one for time), and such distortions define Newton's "force" of gravity–spacetime is actually curved. Because of this curvature, a beam of light passing near the sun would bend in the gravity of a massive object. Experimentally, it was found by Arthur Eddington during the 1919 eclipse that indeed light was bent as it passed by the sun, as predicted by the theory. In 1922, Einstein received the 1921 Nobel Prize, not for his theory of relativity but for the photoelectric effect, a contribution that elucidated one of the two characteristics (duality) of light–a bundle of particles of quantized energy.

Symmetry of Time

Even if we consider the "normal world" when velocities, masses, lengths, and time are with no corrections–Newtonian Limits–and spacetime with no curvature, we still have problems with time, its direction and uncertainty. First let us consider the symmetry of time. Can time go forward and backward, or does it have a direction, an arrow?

In Newton's world, the motion of objects, like you and me, should follow "symmetry of time", that is, the equations describing motion on say the human scale, or that of the Earth around the sun, are time symmetric. There is no difference in the way they work if we make the direction of time go "forward" or "backward". Newtonian mechanics are deterministic and time symmetric. Because the force is related to the mass and the acceleration [$F=ma=m(d^2x/dt^2)$], the equation works equally well for positive and negative time. So, calculating the future of a physical system from its present situation is the same as calculating its past physical situation from its present one–weird and contrary to our common sense. What about microscopic systems, for example the world invisible to the eye–the atom.

For quantum systems, the equation of motion also has invariance under time reversal insofar as the positions of microscopic particles are concerned. This is true despite the deceptive appearance of a first derivative in the Schrödinger wave equation that would imply time reversal. If you can magnify a box containing a gas and see the atoms hitting each other individually you will conclude that there is no arrow of time for every pair of collisions. So, in Newton's mechanics and quantum mechanics, time flows in both directions, making the apparent confusion for the meaning of past, present, and future! In our life, we feel the passage of time and we also know that matter is made of atoms, so we have a dilemma.

Arrow of Time

Phenomena in our life follow an arrow of time. A cup of hot water with a piece of ice displays melting of the ice–the ice does not spontaneously reform again; heat always flows from a hotter object to a cooler one, and not the reverse. An egg breaks when it hits the floor, but it cannot be reformed from the floor. These and similar phenomena are described by the most powerful law, or what Arthur Eddington called the "supreme law of Nature"–the second law of thermodynamics. In one way it describes the arrow of time. In another way, it tells us about the content of information–there is a natural tendency for systems in change to become less ordered or more disordered. A measure of this change is called entropy which is defined as a negative measure of information. Entropy always increases (or at best does not change), order decreases, information decreases, and complexity decreases.

But this loss of information and increase in entropy is for the so-called closed systems (the ice and hot water form a closed system). In some cases, order is created of disorder, and it appears at first that this is in violation of the law of entropy. The tree is a good example–light from the sun, soil and water, and by photosynthesis we have an ordered tree. The Earth is not a closed system and is a part of the solar system–the local decrease in entropy for the tree is compensated for by the way solar (and other) energy change its entropy, and for the solar system on a whole, entropy is increasing according to the second law.

If entropy is always increasing in our universe and the arrow of time is well defined from past to future, why do individual particles, constituents of matter, follow trajectories that are symmetric in time? Put another way, why for a collection of particles each obeying time-reversal symmetry the ensemble as a whole defines an arrow of time? Imagine a box divided into two halves with a partition, one half contains a gas and the other is empty. If we remove the partition the gas will move and fill the whole box. Entropy increased and it appears that we can never reverse the process–we cannot make the gas go into one half and then reinstall the partition to acquire the originally ordered state. In the gas box each particle has a trajectory that follows Newton's mechanics. With time being symmetric, why then does the collection of these particles make the time unsymmetrical? This is a debatable subject and there are different views, one I find particularly interesting.

Time scales and recurrences in time

In the nineteenth century, Henri Poincaré considered this problem of a gas in a box, with all possible arrangements of the particles. He concluded that the system, *if we wait long enough*, will return back to the initial state. The time for this Poincaré recurrence is vastly different depending on the system under consideration. For the gas in the box, the recurrence time for reordering all particles is longer than the age of the universe, but for the vibrational motions of atoms and molecules it could be a millionth of a millionth of a second. This concept of time scale could explain the apparent behavior of systems, reversible or irreversible, depending on complexity and the number of possible arrangements or configurations.

This view is perhaps most clearly demonstrated on quantum systems with time scales short enough that we can experiment with them. If we take the same gas in the box and replace the hypothetical particles with shaped molecules we can perform an interesting experiment. To start with, we already know that there is no order in orientation of molecules and entropy is maximum. We now preferentially excite some of these molecules with their head and tails oriented roughly north and south of the box (we can do so in the laboratory with lasers). If the laser is ultrashort in duration (this too we can achieve in the laboratory) the induced ordered orientation of the molecules will ultimately be maximum at time zero and will decay with time. We call this process of degrading order dephasing, as the whole ensemble of millions of molecules prepared becomes out of step (phase) with each other. However, if we wait for some time, the molecules will acquire back the initial orientation giving rise to Poincaré's recurrences.

Such recurrences have been observed in our laboratory and on an ensemble of millions of molecules. Furthermore, these molecules are complex in their structure and internal motions and experts will tell you that these recurrences should not occur in such systems. But this is not true, as the energy levels are commensurate or nearly so even in complex systems. The recurrences are spaced long enough in time that depending on the time scale of observation the behavior of the system will appear differently. If the time scale of observation is too short, the system would appear irreversible in its decay behavior, but if we wait until recurrences occur we can then see the reversibility behavior.

Irreversibility becomes apparent if the system is not isolated. When the system interacts with a foreign perturber (such as collisions with other molecules–a heat bath) then such recurrences become weak and the system appears irreversibly disordered. Thus without designed methods for introducing order (coherence) to the system and/or without probes for observing its time evolution of disorder (dephasing) we may be misled about the nature of the dynamics. This is critical for defining the meaning and control of complexity and the time scale for reversible/irreversible behavior. We shall come back to this point when we consider measurement of time and matter's time scale.

The above consideration of microscopic/macroscopic behavior considers the origin of irreversible behavior in large ensembles as due to statistical "averaging." As such the law of entropy increase becomes a statistical law. To Ilya Prigogine, however, the second law of thermodynamics is a fundamental law describing irreversibility of nature–the gas in the box will never rearrange again and the ice in the hot cup will never reform, no matter how long we wait. We are now entering a risky area of interpretations and I prefer to stop here until we see further experimental proof! What about the behavior of individual atoms in molecules and their time scale? And, can we observe them moving with order in the ensemble?

At the Limit of Time–Democritus' Atom

The motion of atoms in molecules is fundamental to all dynamic changes of matter, whether the change is physical, chemical, or biological. But these atoms move with awesome rapidity and on ultrashort scales of time and length. On these scales, it is not clear that we can treat them as real, classical objects. Clearly, we must measure the passage of time for atoms on the time scale of the motion, and we must develop the concepts for understanding localization of atoms in space and time. Can this be achieved at the limit of time for quantum atomic motions? If we do, we will then observe Democritus' atom in motion and as a real object, making the transformation from the microscopic (wave function description) to the macroscopic (particle description) a reality in real time.

At Caltech, we have been interested in this endeavor of developing ultrafast laser light to freeze the motion of atoms, to make a motion-picture film of molecules with a frame resolution of a femtosecond. A femtosecond is a millionth of a billionth of a second. In one second, light travels 300,000 km (186,000 miles), almost the distance from the Earth to the Moon; in one femtosecond, light travels 300 nanometers, 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 France, Étienne-Jules Marey, a professor at the Collège de France, was working (1894) on a solution to the problem of action photography using *chronophotography*, a regularly timed 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 applied his chronophotographic apparatus in particular to humans and animals in motion, and to a subject that had puzzled people for many years: the righting of a cat as it falls so that it lands on its feet. How does the cat do it? Does its motion violate Newton's laws of mechanics? Does the cat have some special, magical physiology or a command of some weird new physics or what?

By "slicing time" and freezing the motion during the fall, in the transition state of the righting, Marey was able to answer the questions. First, the cat rotates the front of its body clockwise and the rear part counterclockwise, a motion that conserves energy and maintains the lack of spin, in accordance with Newton's laws. It then pulls in its legs, reverses the twist, and with a little extension of the legs, it is prepared for final landing. The cat instinctively knows how to move, and high divers, dancers, and some other athletes learn how to move in the absence of torque (the pushing force that gives you momentum in one direction or another). However, scientists needed photographic evidence of the individual stopped-action steps to understand the mystery. The answer to the puzzle was that the moving body was not rigid, and Newton's laws prevailed. At the time, these observations were thought-provoking and renowed scientists discussed in public their meaning and significance. J. Willard Gibbs gave a talk on 4 December 1894 before the Mathetical Club at Yale with the title "On motions by which falling animals may be able to fall on their 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. The contrast in *length* and *time* scales for the motion of the cat and the atom is awesome (Figure 2).

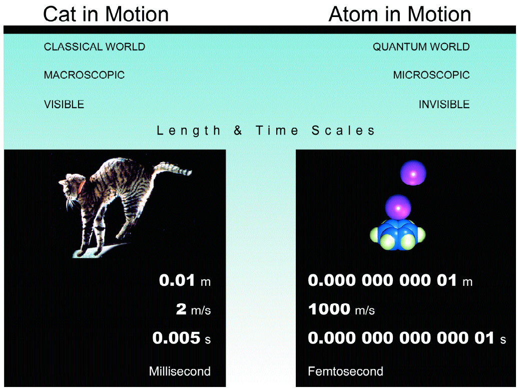

Figure 2. Length and time scales of atoms and cats.

For a definition of 1 cm, a cat speeding at 2 m/s requires a time resolution of 0.005 second. But for a molecular structure in which atomic motions of a few angstroms (an angstrom, Å, is 10^{-8} cm) typically characterize chemical change, a detailed mapping of the motion 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 atoms in motion at a speed 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. Although this was a central idea in the development of femtochemistry, we had to overcome a major dogma regarding the uncertainty principle!

Solving the Riddle of Uncertainty–Physics

For the atom such minute time and distance scales 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. Werner Heisenberg in the 1920s discovered that for quantum systems we are not allowed to make a precise measurement of both the position (x) and the momentum (p) of a particle at the same time. This tells us that we are losing knowledge – we do not know exactly where it is and where it is going (future), simultaneously, that is, the more accurately we determine one of these conjugates the more information we lose on the other. There is intrinsic uncertainty! Similarly, if we can measure the energy (E) of a system very precisely we cannot obtain the same precision for time (*t*) simultaneously. There is uncertainty in the measurement of time depending on how accurate the energy is, and the consequences are important for all sciences on the ultrashort time scale.

These considerations of uncertainties led initially to the belief that the femtosecond time resolution would not be useful. Moreover, predictions suggested that localization of atoms in space–wave packets–would not be possible to sustain for a long time, even on the femtosecond scale. Finally, there is a fundamental difference in the analogy between femtosecond stop-motion action of atoms and the millisecond photography of a cat or horse-in femtochemistry experiments one probes typically millions to trillions of molecules, and/or repeats the experiment many times to provide a signal strong enough for adequate images. Unlike experiments on one cat or one horse, the picture for an ensemble of molecules would be blurred.

We accommodate this by recognizing two of the most powerful and yet indigestible concepts: the uncertainty principle and the particle-wave duality of matter (de Broglie, 1924). The complementary aspect of these two descriptions is interwoven with the concept of coherence. Two or more waves can produce interference patterns when their amplitudes add up coherently. For matter, superpositions analogous to those of light waves can be formed from matter wavefunctions. The Schrödinger equation yields wavefunctions together with their probability distributions, which are diffuse over position space. But if these waves are added up coherently with well-defined phases, the probability distribution becomes localized in space. The resultant wave packet and its associated de Broglie wavelength has the essential character of a classical particle: a trajectory in space and time with a well-defined (group) velocity and position–a moving classical marble but at atomic scale.

To see motion in real systems, localized wave packets must form in every molecule, and there must also be a limited spread in position among the wave packets formed in the millions of molecules studied. This is achieved by the well-defined initial equilibrium configuration of the molecules before excitation and by the "instantaneous" femtosecond launching of the packet. The spatial confinement of the initial ground state, typically 0.05 Å, ensures that all molecules, each with its own coherence, begin their motion in a bond-distance range much smaller than that of the actual motion, typically 5^{-10} Å. The femtosecond launching ensures that this narrow range of bond distance is maintained throughout preparation. With coherent and synchronous preparation, the motion of the ensemble becomes that of a single-molecule trajectory.

In 1987, we reached our goal of observing, for the first time, Democritus' atom—theorized by the Greek philosopher some 2500 years ago–in motion, and we could describe it on the femtosecond time scale as a classical object like the cat and horse (Figure 3). 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.

Eugene Wigner and Edward Teller debated the uncertainty paradox for picosecond time-resolution in a lively exchange at the Welch Conference in 1972. However, because of coherence, the uncertainty paradox is not a paradox even for femtoscience, and certainly not for the dynamics of physical, chemical, and biological changes. Charles Townes encountered objections in the realization of the maser because of concern about the uncertainty principle, but coherence was again the key to success. As we cross the femtosecond barrier into the attosecond regime for studies of electron dynamics, we must recall this vital role of coherence. Otherwise the spectre of quantum uncertainty might veil the path to new discoveries.

In retrospect, this vital role of coherence in the uncertainty paradox and the fog that surrounded its utility should have been clear (Figure 3 and bibliography). We and others have considered in detail the theoretical quantum calculations of molecular systems and indeed confirmed the localized motions of atoms. But, the physical origin of the behavior is simple to understand. Considering the uncertainty in the position to be Δx, and similarly for the other variables, the two uncertainty relations,

$$\Delta x \, \Delta p \geq \hbar /2$$

$$\Delta t \, \Delta E \geq \hbar /2$$

show that the only way to localize atoms (small Δx) is by shortening time (Δt). Moreover, when Δt is on the femtosecond time scale, even a discrete quantum system, if excited coherently, becomes effectively a continuum or quasi-continuum of energy states, which represents a transition to the classical world.

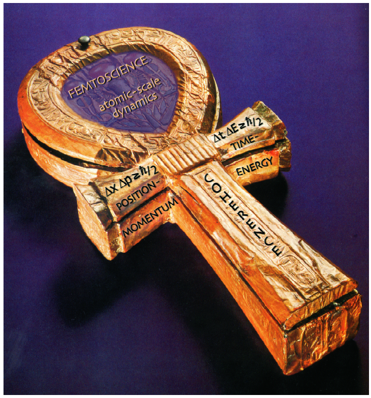

Figure 3. Uncertainties and unification through coherence.

Given that we can localize a system to an initial distance of Δx_o at time zero, why does the system remain coherent and behave as a classical object? And, does the time for the loss of coherence depend on the size of the object? Because the value of $\hbar$ is very small, this time depends crucially on the size. To see this clearly, we must recall that the uncertainty relation relates the uncertainty in position (Δx) to the uncertainty in momentum (Δp); but it is the velocity, and not momentum per se, which tells us the future position. Since $\Delta p = m\,\Delta \mathrm{v}$, it follows, from the uncertainty relation, that $\Delta \mathrm{v} = \hbar / (2m\,\Delta x_o)$–the larger the size (the larger the mass m and also the larger the scale of precision in position Δx_o) the smaller the uncertainty in velocity (Δv) and the better we are in predicting the future. Now it is straightforward to calculate the "time of uncertainty" which tells us how long it will be before the uncertainty in velocity will contribute as much to our lack of knowledge of where the object is as that which came from the original position uncertainty (Δx_o):

$$t\ (\text{uncertainty})=\Delta x_o/\Delta \text{v}=2m\ \Delta x_o^2\ /\ \hbar$$

Beyond this time scale, the uncertainty, due to our lack of knowledge of velocity, makes us less certain of the future and the description of the object becomes quantum, not a classical one. This simplified equation can be obtained from a more rigorous treatment of wave packet motion, and elsewhere we did so.

The size of $\hbar$, 1 x 10^{-27} erg-sec, means that the fuzziness required by the uncertainty principle is imperceptible on the normal scales of size and momentum, but becomes important at atomic scales. For example, if the position of a stationary 200-g apple is initially determined to a small fraction of a wavelength of light, say $\Delta x_o = 10$ nm, the apple's position uncertainty will spread by about 40% only after 4×10^{17} s, or 12 billion years, that is, the age of the universe! On the other hand, an electron with a mass 29 orders of magnitude smaller would spread by 40% from an initial 1-Å localization after only 0.2 femtosecond.

From atom to man, the time and length of uncertainty determine the classical-quantum description of motion (Figure 4). The time scale for future uncertainty runs from femtoseconds for the hydrogen atom, to 300 years for biological cells, and to more than the age of the universe for humans–we have 300 years (or more) to behave in a deterministic classical world, so biotechnologists can be sure to improve the human life expectancy by at least three times from the current one without the need of new mechanics!

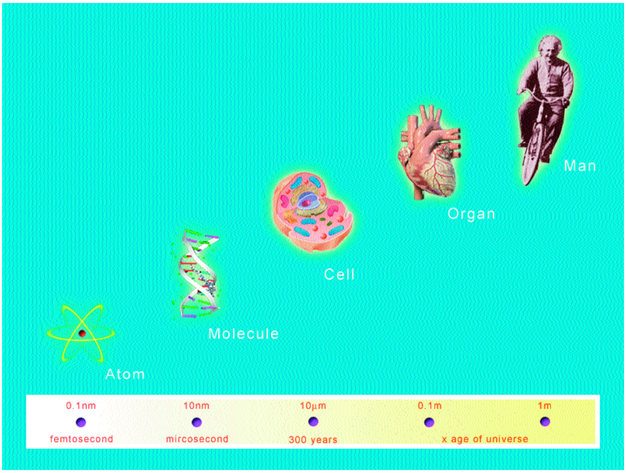

Figure 4. From Atom to Man-length scale and time of uncertainty.

The Molecular World–Chemistry

Conceptually, our work in the late 1970s on coherence phenomena and in the mid 1980s closing in to resolve reaction dynamics in real time provided the foundation for thinking about the issues raised above. It became clear that molecules can be made to vibrate coherently and ensembles of molecules can be made to behave in unison. Experimentally, we needed a whole new apparatus, a whole new "camera" with unprecedented time resolution. We needed to interface femtosecond lasers and molecular-beam technology, which required not only a new initiative but also a major effort at Caltech. In a relatively short time, femtochemistry research became active in many laboratories around the world.

The breadth of applications emerging spans the 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 made at Caltech on a sibling of table salt (two atoms) and another 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 remarkably coherent and highly efficient first step of vision at the atomic level.

Complexity–Biology

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 in femtobiology are those concerned with the conduction of electrons in the genetic material, the binding of oxygen to hemoglobin (myglobin) and its mimics, molecular recognition of protein by drugs, and the molecular basis for the cytotoxicity of anticancer drugs, and of digestion.

A current major problem of interest is the role of water in biological systems–biological water. The pertinent question is: How does the interaction of water molecules with proteins and DNA influence the biological function? In a series of papers we have reported our studies of interfacial water dynamics and the unique role the dynamics play in the function. We are also developing new techniques to observe the behavior and architecture of these complex molecules–in space and time–using diffraction images, which give the 3-D location of all the atoms, all at once. But now a fourth dimension–time–is introduced to see how complex systems behave during the function. The new methodology, which we termed ultrafast electron crystallography (and microscopy), is now established with many applications (see bibliography). The impact on biology and medicine is clear.

Life is a manifestation of complexity in which atoms of the microscopic world combine in different ways to form functional systems with enormous diversity and unique information. And that is what makes the human "intermediate scale" (Figure 1) special–on one hand simple in function and on the other hand rich in complexity. Deciphering this complexity and reducing its meaning to the atomic motions involved is one of the most fundamental problems of this century.

Technology of Femtoscience

As for technology developments–femtotechnology–there are exciting new developments in microelectronics (femtomachining), femtodentistry, and femtoimaging (microscopy) 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 scales of time and length. 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. There is also the possibility for controlling matter on the femtosecond time scale–one day we may direct chemical reactions into specific or new products.

Epilogue

I wish to conclude by conjecturing on some future mysteries and miracles of time. In the physical sciences, one advance that surely will allow us to reach the electron domain involves measurements on the sub-femtosecond time scale. Now the average energy is nearing the x-ray region, much above chemical and biological energies, and the pulse width is larger than chemical binding energies. Nonetheless, such advances will make it possible to study electron dynamics in many domains of physics and related areas.

In the life sciences, the advent of diffraction and microscopy techniques with atomic-scale spatial and temporal resolution will undoubtedly lead to a revolution in structural dynamics of biomolecules, building real bridges between structures, dynamics and functions (see bibliography).

In cosmology, Planck's scale of time, the nature of spacetime, and the arrow of time are subjects that will remain in need of further discovery and search for meaning.

From the very small (atom), to the very complex (life), to the very big (universe), despite some mysteries, new frontiers will be reached with time defining a fundamental dimension. Perhaps the biggest of all challenges is reversal of time. Ever since H.G. Well's novel "The Time Machine," the human imagination has considered the possibility of reversing the arrow of time, going back in time. In theory we could, but the paradoxes are many. A time traveler may go back in time and alter circumstances leading to his own existence or lack thereof. Two-way time travel is indeed weird, and may force an entry to the world of weird physics! So despite its miracles and the impact on our life, we still struggle with the meaning of time.

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Zewail, A.H. 2001. The Uncertainty Paradox–The fog that was not. Nature, London, 412, 279.

Zewail, A.H. 2002. Voyage Through Time–Walks of Life to the Nobel Prize. American University Press, Cairo (also in 12 editions and languages).

Zewail, A.H. 2005. Diffraction, Crystallography, and Microscopy Beyond 3D–Structural Dynamics in Space and Time. Philosophical Transactions, Royal Society, 364, 315.

BIOGRAPHY

Winner of the 1999 Nobel Prize in Chemistry, Ahmed H. Zewail was born in Demanhur, Egypt, on 26 February 1946. He studied at the University of Alexandria before moving to the USA to complete his PhD at the University of Pennsylvania. Following post-doctoral work at the University of California at Berkeley, he accepted a post at Caltech in 1976, and subsequently took the first Linus Pauling Chair in Chemical Physics at that institution.

Dr. Zewail has been at the forefront of the field of femtochemistry, which is the study of chemical reactions within extremely short intervals of time: femtoseconds. He has pioneered the use of ultrafast lasers and electrons to study chemical reactions at atomic level, a technique which has had profound implications for chemistry and biology. At present, the Center Dr. Zewail heads is devoted to new research frontiers in physical biology, exploring the origin of molecular and cellular behavior.

The first winner of a Nobel Prize in science from an Arab country, Dr. Zewail has received numerous awards and holds honorary doctorates from institutions around the world. He is noted for his public lectures and service to humanity. He is married with four children, and lives in San Marino, California.

Academic Positions

2005-present	Director, Physical Biology Center for Ultrafast Science & Technology
1996-present	Director, NSF Laboratory for Molecular Sciences (LMS), Caltech
1995-present	Linus Pauling Professor of Chemistry and Professor of Physics, Caltech
1990-1994	Linus Pauling Professor of Chemical Physics, Caltech
1982-1989	Professor of Chemical Physics, Caltech
1978-1982	Associate Professor of Chemical Physics, Caltech
1976-1978	Assistant Professor of Chemical Physics, Caltech

1974-1976	IBM Postdoctoral Fellow, University of California, Berkeley
1970-1974	Predoctoral Research Fellow, University of Pennsylvania
1969-1970	Teaching Assistant, University of Pennsylvania
1967-1969	Instructor and Researcher, Alexandria University
1966	Undergraduate Trainee, Shell Corporation, Alexandria

Professorships

1979	University of Amsterdam, John van Geuns Stichting Visiting Professor, Holland
1981	University of Bordeaux, Visiting Professor, France
1983	Ecole Normale Supérieure, Visiting Professor, France
1987	University of Kuwait, Visiting Professor, Kuwait
1988	University of California, Visiting Scholar, Los Angeles, U.S.A.

1988 American University in Cairo, Distinguished Visiting Professor, Egypt

1990 Johann Wolfgang Goethe-Universität, Rolf Sammet Professor, Frankfurt, Germany

1991 Oxford University, Sir Cyril Hinshelwood Chair, Visiting Professor, Oxford, U.K.

1992 Texas A&M University, Visiting Professor, U.S.A.

1992 University of Iowa, Visiting Professor, U.S.A.

1995 Collège de France, Visiting Professor, Paris, France

1998 Katholieke Universiteit, Visiting Professor, Leuven, Belgium

1999 University of Würzburg, Röntgen Visiting Professor, Germany

2000 Université de Lausanne, Honorary Chair Professor, Switzerland

2002 University of Cambridge, Linnett Professorship, United Kingdom

2003-present United Nations University, Distinguished Chair of Science & Technology Policy, Tokyo, Japan

2004-present Huazhong University, Honorary Professorship, Wuhan, P.R. China

2004-present Fudan University, Honorary Professorship, Shanghai, P.R. China

2004/2005 Ecole Normale Supérieure, Blaise Pascal Honorary Professorship, France

2005 Tohoku University, First Honorary University Professor, Sendai, Japan

Academic Degrees

1967 Alexandria University, Egypt; B.S., First Class Honors

1969 Alexandria University, Egypt; M.S.

1974 University of Pennsylvania, Philadelphia, U.S.A. Ph.D.

Honorary Degrees

1991 Oxford University, United Kingdom; M.A., h.c. (Arts)

1993 American University in Cairo, Egypt; D.Sc., h.c. (Science)

1997 Katholieke Universiteit, Leuven, Belgium;
D.Sc., h.c. (Science)

1997 University of Pennsylvania, U.S.A.;
D.Sc., h.c. (Science)

1997 Université de Lausanne, Switzerland;
D.Sc., h.c. (Science)

1999 Swinburne University, Australia;
D.U., h.c. (University)

1999 Arab Academy for Science & Technology, Egypt;
H.D.A.Sc. (Appl. Science)

1999 Alexandria University, Egypt;
H.D.Sc. (Science)

2000 University of New Brunswick, Canada;
D.Sc., h.c. (Science)

2000 University of Rome "La Sapienza", Italy;
D., h.c. (Doctor)

2000 Université de Liège, Belgium;
D., h.c. (Doctor)

2000 Queen of Angels-Hollywood Presbyterian Medical Center; Honorary Member of the Medical Staff, U.S.A.; M.D. (Medicine)

2001	Jadavpur University, India; D.Sc., h.c. (Science)
2002	Concordia University, Montréal, Canada; LLD, h.c. (Law)
2002	Heriot-Watt University, Scotland; D.Sc., h.c. (Science)
2003	Pusan National University, Korea; M.D., h.c. (Medicine)
2003	Lund University, Sweden; D.Ph., h.c. (Philosophy)
2003	Boğaziçi University, Istanbul, Turkey; D.Sc., h.c. (Science)
2003	Ecole Normale Supérieure, Paris, France; D.Sc., h.c. (Science)
2004	Oxford University, United Kingdom; D.Sc., h.c. (Science)
2004	Peking University, People's Republic of China; H.D.D. (University)
2004	Autonomous University of the State of Mexico, Toluca, Mexico; D., h.c. (University)

2005 University of Dublin, Trinity College; Ireland D.Sc., h.c. (Science)

2005 Tohoku University, Sendai, Japan H.D.D. (University)

2005 American University of Beirut, Lebanon; D. H. L. (Humane Letters)

2005 University of Buenos Aires, Argentina; D., h.c. (University)

2005 National University of Cordoba, Argentina; D., h.c. (University)

Honorary Fellowships, Academies, and Societies

- American Physical Society, Fellow (elected 1982)
- National Academy of Sciences, U.S.A. (elected 1989)
- Third World Academy of Sciences, Italy (elected 1989)
- St. Catherine's College, Fellow, Oxford, U.K. (elected 1991)
- Sigma Xi Society (elected 1992)
- American Academy of Arts and Sciences (elected 1993)
- Académie Européenne des Sciences, des Arts et des Lettres, France (elected 1994)

- American Philosophical Society (elected 1998)
- Pontifical Academy of Sciences (elected 1999)
- American Academy of Achievement (elected 1999)
- Royal Danish Academy of Sciences & Letters (elected 2000)
- American Association for the Advancement of Science, AAAS, Fellow (elected 2000)
- Chemical Society of India, Honorary Fellow (elected 2001)
- Indian Academy of Sciences, Banglore, India (elected 2001)
- The Royal Society of London, Foreign Member, U.K. (elected 2001)
- Sydney Sussex College, Honorary Fellow, Cambridge, U.K. (elected 2002)
- Indian National Science Academy, Foreign Fellow, New Delhi, India (elected 2002)
- Korean Academy of Science and Technology, Honorary Foreign Member (elected 2002)
- African Academy of Sciences, Honorary Fellow, Nairobi, Kenya (elected 2002)
- Royal Society of Chemistry, Honorary Fellow, U.K. (elected 2003)

- Russian Academy of Sciences, Foreign Member (elected 2003)
- The Royal Swedish Academy of Sciences, Stockholm, Foreign Member (elected 2003)
- The Royal Academy of Belgium, Brussels, Foreign Member (elected 2003)
- St. Catherine's College, Honorary Fellow, Oxford, U.K. (elected 2004)
- European Academy of Sciences, Honorary Member, Brussels, Belgium (elected 2004)
- The Literary & Historical Society, University College, Honorary Fellow, Dublin, Ireland (elected 2004)
- The National Society of High School Scholars, Honorary Member Board of Advisors, Atlanta, Georgia, U.S.A. (elected 2004)
- Academy of Sciences of Malaysia, Honorary Fellow (elected 2005)
- French Academy of Sciences, Foreign Member (elected 2005)

Special Honors

1989	King Faisal International Prize in Science
1990	First Linus Pauling Chair, Caltech
1993	Femtochemistry Conferences; Solvay, Nobel, and Int'l. series
1993	Wolf Prize in Chemistry
1995	Order of Merit (OM) from President M. H. Mubarak, Egypt
1997	Robert A. Welch Award in Chemistry
1998	Benjamin Franklin Medal, The Franklin Institute, U.S.A.
1998	Dr. Ahmed Zewail High School, Disuq City
1999	Egypt Postage Stamps, with Portrait; "The Fourth Pyramid"
1999	Nobel Prize in Chemistry
1999	Order of the Grand Collar of the Nile, Highest Honor of Egypt, conferred by President Mubarak
2000	Order of Zayed, Highest Presidential Honor, State of United Arab Emirates

2000 Order of Cedar, Highest Rank of Commander, from President Emile Lahoud, State of Lebanon

2000 Dr. Ahmed Zewail Medan (Square), City of Alexandria

2000 Order of ISESCO, First Class, from Prince Salman Ibn Abdel Aziz, Saudi Arabia

2000 Order of Merit (OM) of Tunisia, Highest Honor from The President of the Republic, Zine El Abedine Ben Ali

2000 Insignia of Pontifical Academy, from Pope John Paul II, Vatican

2000 Ahmed Zewail Fellowships, University of Pennsylvania, U.S.A.

2001 Ahmed Zewail Prize, American University in Cairo

2001 Exhibition, Nobel Museum, Stockholm, Sweden

2001 BBC Documentary

2002 Postage Stamp, issued by the country of Ghana

2002 Ahmed Zewail Center for FemtoScience Technology, Korea

2004 Order of the Two Niles, First Class, Highest State Honor, from President Omar Bashir, Republic of Sudan

2004 Dr. Ahmed Zewail Prize for Creativity in the Arts, Opera Culture Center, Cairo

2004 Zewail Foundation for Knowledge and Development, Cairo

2004 Ahmed Zewail Prizes for Excellence and Leadership, International Centre for Theoretical Physics (ICTP), Trieste, Italy

Selected Awards and Prizes

1978 Alfred P. Sloan Foundation Fellow

1979 Camille and Henry Dreyfus Teacher-Scholar Award

1983 Alexander von Humboldt Award for Senior United States Scientists

1984; 1988;

1993 National Science Foundation Award for especially creative research

1985	Buck-Whitney Medal, American Chemical Society
1987	John Simon Guggenheim Memorial Foundation Fellow
1989	Harrison Howe Award, American Chemical Society
1992	Carl Zeiss International Award, Germany
1993	Earle K. Plyler Prize, American Physical Society
1993	Medal of the Royal Netherlands Academy of Arts and Sciences, Holland
1994	Bonner Chemiepreis, Germany
1995	Herbert P. Broida Prize, American Physical Society
1995	Leonardo da Vinci Award of Excellence, France
1995	Collége de France Medal, France
1996	Peter Debye Award, American Chemical Society
1996	National Academy of Sciences Award, Chemical Sciences, U.S.A.
1996	J.G. Kirkwood Medal, Yale University
1996	Peking University Medal, PU President, Beijing, China
1997	Pittsburgh Spectroscopy Award

1997 First E.B. Wilson Award, American Chemical Society

1997 Linus Pauling Medal Award

1998 Richard C. Tolman Medal Award

1998 William H. Nichols Medal Award

1998 Paul Karrer Gold Medal, University of Zürich, Switzerland

1998 E.O. Lawrence Award, U.S. Government

1999 Merski Award, University of Nebraska

1999 Röntgen Prize, (The 100th Anniversary of The Discovery of X-rays), Germany

2000 Faye Robiner Award, Ross University School of Medicine, New York

2000 Golden Plate Award, American Academy of Achievement

2000 City of Pisa Medal, City Mayor, Pisa, Italy

2000 Medal of "La Sapienza" ("wisdom"), University of Rome

2000 Médaille de l'Institut du Monde Arabe, Paris, France

2000 Honorary Medal, Universite Du Centre, Monastir, Tunisia

2000 Honorary Medal, City of Monastir, from The Mayor, Tunisia

2002 Distinguished Alumni Award, University of Pennsylvania

2002 G.M. Kosolapoff Award, The American Chemical Society, Auburn, Alabama

2002 Distinguished American Service Award, ADC, Washington D.C.

2002 Sir C.V. Raman Award, Kolkata, India

2004 Arab American Award, National Museum, Dearborn, Michigan

2004 Gold Medal (Highest Honor), Burgos University, Burgos, Spain

2005 Slovak Academy of Science Medal, Bratislava, Slovak Republic

2005 Gold Medal, Slovak Chemical Society

2005 Grand Gold Medal, Comenius University, Bratislava, Slovak Republic

2005 Medal of University of Buenos Aires, Argentina

2005 Medal of National University of Cordoba, Argentina

Professional Activities

Member of Advisory and Editorial Boards; Editor of scientific journals (Chemical Physics Letters at present) and book series; Chairman and Member of Organizing Committees of national and international conferences; Member of Boards including the following:

1994-present World Scientific Advisory Board

1994-present Max Planck Institute, Board of Advisors

1999-present American University in Cairo, Board of Trustees

2001-present Bibliotheca Alexandria (The Library of Alexandria), Board of Trustees

2002-present The Welch Foundation, Scientific Advisory Board

2003-present Multilateral Initiative on Malaria, Patron

2003-present	Qatar Foundation, Board of Directors
2003-present	Chalmers University, Scientific Advisory Board, Sweden
2004-present	TIAA-CREF, Board of Trustees
2005-present	Nanyang Technological University (NTU), Advisory Board, Singapore

Publications and Presentations

Some 450 articles have been published in the fields of science (authored and co-authored with members of the research group), education, and world affairs.

The following books have been published:

(1) *Advances in Laser Spectroscopy, Vol. 1* (ed.), SPIE Publishing Co. (1977)

(2) *Advances in Laser Chemistry, Vol. 3* (ed.), Springer-Verlag Series in Chemical Physics (1978)

(3) *Photochemistry and Photobiology, Proceedings of an International Conference, Vols. I and II* (ed.), Harwood Academic Publishers, New York, London, Chur (1983)

(4) *Ultrafast Phenomena VII,* with C.B. Harris, E.P. Ippen, and G.A. Mourou (eds.), Springer Series in Chemical Physics 53, Springer-Verlag, New York (1990)

(5) *The Chemical Bond: Structure and Dynamics* (ed.), Academic Press, Boston (1992)

(6) *Ultrafast Phenomena VIII,* with J.-L. Martin, A. Migus, and G.A. Mourou (eds.), Springer Series in Chemical Physics 55, Springer-Verlag, New York (1993)

(7) *Ultrafast Phenomena IX,* with P.F. Barbara, W. Knox, and G.A. Mourou (eds.), Springer Series in Chemical Physics 55, Springer-Verlag, New York (1994)

(8) *Femtochemistry--Ultrafast Dynamics of the Chemical Bond, Vols. I and II,* World Scientific, New Jersey, Singapore (1994)

(9) *Voyage Through Time--Walks of Life to the Nobel Prize,* American University in Cairo Press (2002); appeared in 12 languages and editions

(10) *Asr Al ấlm,* Dar Al Shorouk, Beirut and Cairo editions (in Arabic) (2005)

The following patent was issued in 1980:
"Solar Energy Concentrator Devices" - Ahmed H. Zewail and J. Samuel Batchelder, disclosed at the California Institute of Technology, 17 April, 1977; U. S. Patent 4,227,939 dated 14 October, 1980.

Some 300 named, plenary, and keynote lectures have been given and include the following: Bernstein, Berson, Bodenstein, Cavendish (Scott Series), Celsius, Condon, Aimé Cotton, Coulson, Debye, Einstein (Berlin, New Delhi), Eyring, Faraday, Franklin (Benjamin), Gandhi, Helmholtz, Hinshelwood, Karrer, Kirkwood, Kistiakowsky, Lawrence, London, Nobel, Novartis, Noyes, Onassis, Pascal (Blaise), Pauling, Perrin, Pimentel, Max Planck, Polanyi, Raman, Roberts, Röntgen, Schrödinger, U Thant (United Nations), Thomson (J.J.), Tolman, Watson, and Wilson. Also given are commencement addresses and public lectures.

Research, Public Education, and World Affairs

Current research is devoted to dynamical chemistry and biology, with a focus on the physics of elementary processes in complex systems. In the Laboratory for Molecular Sciences (LMS) Center, collaborative multidisciplinary research has been established to address the role of complexity in the primary function of real systems including enzyme catalysis, protein-RNA transcription, electron transport in DNA, and the role of water in protein and DNA recognitions. A major research frontier at LMS is the new development of ultrafast diffraction techniques that make possible the imaging of transient structures in space and time with atomic-scale resolution.

A significant effort is also devoted to giving public lectures to enhance awareness of the value of knowledge gained from fundamental research, and helping the population of developing countries through the promotion of science and technology for the betterment of society.

SELECTED PUBLICATIONS

(since the Nobel Prize)

SCIENCE AND TECHNOLOGY

Development of 4D Ultrafast Imaging & Microscopy

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(2) The Uncertainty Paradox – The Fog That Was Not. A.H. Zewail, *Nature* (London), **412**, 279 (2001)

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