Light and life*

Ahmed Zewail

In this country there is a tradition of prime ministers appreciating and supporting science and technology. From Pandit ('teacher') Jawaharlal Nehru to Indira Gandhi and to Rajiv Gandhi all have shown a commitment to scientific research and its critical role in developing the mind, the society, and the nation. Abdul Kalam, a prominent technologist, is the current President. Rajiv Gandhi believed in extending the science base and not to limit it to a privileged few. In one of his speeches he said, scientific research 'must be supported by a very broad base of people who have scientific learning from which we can draw and reach out to the best people available. We have got pillars that reach to great heights, but they remain pillars – we have to turn them into pyramids'. Incidentally, by mentioning the word *pyramids* in his speech in Delhi, he anticipated by 16 years that an Egyptian, who also believes in building pyramids, would be invited to give the lecture honouring his contributions!

Scientific research is the subject of this lecture, but I wish to focus here on one of its pillars – the value of curiosity-driven research and its impact on our life, the life of the 'haves' and 'have-nots'. For this scientific endeavour, I will demonstrate my point from the study of one phenomenon that has occupied the thinking of humans throughout history – it is the phenomenon of light. What is light?

Twelve billion years ago, give or take a few billion, the big bang took place. In this process at the earliest time, light was an integral part of the creation of the universe. In our galaxy the sun has given light for 4.6 billion years; astronomers tell us that in 10 billion years the sun will shrink and become white hot, a white dwarf, and eventually a dark dwarf – the star will be dead and life here will end. For millions of years, light has defined the life of *Homo sapiens*. Through photosynthesis, light has given us food, energy, and the atmosphere. And using light we communicate information, see the big objects (planets and moons) far from us in the vault of the heavens, and see the small microscopic objects (cells and bacteria) our naked eye cannot resolve. Our life becomes invisible without light. From where does light get this transcending power?

People of ancient civilizations believed in light's miraculous power, a mighty power that deserved to be worshipped. The Egyptians had the first single god, the god of the sun-disk Aton (under the pharaoh Akhenaton), and Hindu teachings repeatedly highlight light and en-*light*-enment. A millennium ago, one of the most important scientific advances made in the study of light was that put forward by the Muslim scientist ibn al-Haytham (ca. 965–1038), known in the West as Alhazen and acknowledged to be the greatest scientist of the European Middle Ages. He was the conceptual pioneer of *camera obscura* and his ideas about light and vision were revolutionary: light must travel in a straight path, at a high speed, and light reflects from bodies and refracts in media; our vision is the result of reflecting light to the eyes, and *not* by emitting light from them. Alhazen began with his observations of and experiments with light, then reasoned towards a theory. Alhazen's masterpiece, *Kitab al-Manazir* (*Treatise on Optics*), remained in Western Europe as the primary work on optics for more than half a millennium and up to the time of Kepler and Newton and even later.

It took nearly a millennium until James Clerk Maxwell in 1864 gave the world the first quantitative description of what light is made of – waves of disturbances of elec-

*Based on the Rajiv Gandhi Science Lecture delivered on 17 October 2002 at Bangalore.

Ahmed Zewail is Linus Pauling Professor of Chemistry and Physics, Laboratory for Molecular Sciences, Arthur Amos Noyes Laboratory of Chemical Physics, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA91125, USA.
(e-mail: zewail@caltech.edu)

tric and magnetic fields. These waves move in space and through time. Furthermore, Maxwell's equations predict the correct high speed of light (c = 300,000 km/s), which was first estimated in 1675 by the Danish astronomer Olav Roemer and measured in 1849 by the French scientist A.-H.-L. Fizeau. In elucidating that light is an electromagnetic wave, Maxwell unified the important work of Michael Faraday (1791–1867) on electricity and magnetism and of Thomas Young on the wave nature of light (interference; 1801). As a wave, light has a wavelength (λ) and frequency ($\nu = c/\lambda$) – this is true for all waves of the entire electromagnetic spectrum, from radio waves to X-rays. With Maxwell's breakthrough, scientists of the day thought that the question of the nature of light was answered conclusively, but there was a surprise in store.

At the beginning of the twentieth century, physics witnessed the development of two revolutionary ideas – quantum mechanics (1900) and relativity (1905) – suggesting that in the world of the very small (atoms) and the world of the very large (with very high mass or very high velocity) Newtonian mechanics would not apply, a real blow to centuries of belief.

In 1905, Albert Einstein recognized the implications of quantization for light – it is made of a stream of particles and comes as bundles of energy ($E = h\nu$) – the light quanta, called by G. N. Lewis as *photons*. The particle description had been advanced by Isaac Newton (1643–1727) and other scientists even earlier, but in Einstein's view the energy (E) and frequency are related by Planck's constant (h). Einstein was successful in using 'this bundling-of-energy' concept to explain the ejection of electrons from metal surfaces, the photoelectric effect, for which he received the Nobel Prize in Physics – *not* for his theory of relativity! With quantization it was possible to explain a variety of phenomena, including the Raman effect, named after the famed Indian physicist C. V. Raman, who in 1928 observed the scattering of monochromatic light as it passes through a transparent substance.

Considering the two descriptions of light by Maxwell and Einstein, we now view light as behaving partly like (electromagnetic) waves and partly like particles – a duality in its nature! Until today we do not fully understand the meaning of this duality, nor do we really understand quantum mechanics, with its uncertainty, as we do the classical mechanics of Newton, with its deterministic laws of motion. But we know how to operate with the dualistic wave-type and particle-type behaviour of light. Remarkably, the same duality was found for all matter at the microscopic level, and now we speak of atoms as particles and as waves: the momentum (p) of a particle is related to its wavelength by the well-known de Broglie relationship ($\lambda = h/p$).

Why are these new concepts important? Besides being brain-teasing, thought-provoking ideas, they provide the springboard for advances in technology. Without quantum mechanics we would not have developed the transistor, the semiconductor industry, and the computer revolution. Neither would we have had the laser, optical communication, and the age of information technology. There would be no global economy to speak of. It is said, notably, that more than half of the US economy is based on quantum mechanics. Without quantum mechanics, we would not be able to tune the radio or communicate with a satellite or position a spaceship – we must know the frequency of the waves used and know how to communicate with them using quantum devices. And we must know the frequency and intensity of this bundle of energy, the photons, to perform eye surgery with lasers.

But there is more. Progress in science is made through paradigm shifts to develop new concepts and new techniques. With optical elements such as lenses and mirrors, light does magic, bringing into focus the world of the very small, the very far, and the ephemeral. 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 light 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 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, ships in the distance and then the heavens. Through scientific observations (1610) of Jupiter's moons, which revolve around a planet other than the earth, Galileo refuted the long-held dogma of geocentrism, proving that the stationary earth is *not* at the centre 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 centre of the universe and the planets, including the 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 concepts and techniques we could not launch a spaceship or a satellite or hope to understand our universe.

Galileo used his telescopic observations along with other empirical data to understand mechanics in general and falling bodies in particular. He provided a new way to test a hypothesis and he refuted Aristotle's theory that heavier bodies fall faster than lighter ones. The 'mechanical philosophy' of interacting particles, or 'corpuscles', elucidated by René Descartes (1596–1650), and the concept of the 'mechanical universe' – synthesized in Newton's magnum opus *Mathematical Principles of Natural Philosophy* (1687) – provided the basis for thinking about motion and the mechanics of macroscopic objects.

In contrast, motions in the microscopic world – *the quantum world* – had never been observed in real time because the human eye responds in the slow sweep of a fraction of a second, while microscopic motions charge along at a faster rate than the eye is capable of. These microscopic motions are 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. We needed what we have termed a *femtoscope*, and as with the ordinary light microscope and the telescope, light is the essential element.

At Caltech, we have been interested in this endeavour of developing ultrafast laser light to construct a femtoscope capable of freezing the motion of atoms, to make a motion-picture film with a frame resolution of a femtosecond. A femtosecond is a millionth of a billionth of a second, i.e. 0.000 000 000 000 001 s. You can see that without the Indian zero and Arabic numerals we would not have been able to express in numerical terms the meaning of a femtosecond! A femtosecond is to one second as a second is to 32 million years. 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 nm (0.000 000 3 m), 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), but 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. Marey's work and that of Eadweard Muybridge on the horse have changed the way we think of the behaviour 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 timescale. The contrast in *length* and *timescales* for the motion of the cat and the atom is awesome. For a definition of 1 cm, a cat speeding at 2 m/s requires a time resolution of 0.005 s. 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 with a speed of 1 km/sec (1000 m/s) is 0.1 Å divided by 1000 m/s, which equals 10^{-14} s or 10 fs – a million million times shorter than what was needed for Marey's (or Muybridge's) stop-motion photography.

However, such minute time and distance scales for the atom 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 the horse. In quantum mechanics, the uncertainty principle between position in space and momentum, and similarly between time and energy, 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 femtoscopy of the atom and the millisecond photography of the cat or horse in that 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 horse, the picture would be blurred.

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 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 timescale as a classical object like the cat and the 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.

Historically, coherence was also not appreciated in the realization of the maser (*m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation). A pioneer in the development of the maser, Charles Townes, who gave the Rajiv Gandhi lecture in 1997, initially encountered objections to his idea that electronomagnetic waves could be made 'purely' monochromatic, objections based on the uncertainty principle. The claim was that since molecules would spend only about one ten-thousandth of a second in the cavity of a maser, it would be impossible for the frequency of the radiation to be narrowly confined. In the event, coherence of photons in the stimulated emission-feedback process removed this concern, and first the maser and later the laser were developed.

With the femtoscope, the breadth of applications emerging from all over the world 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.

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 haemoglobin, 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 behaviour and architecture of these complex molecules – in space and time – using diffraction images, which give the 3D 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 tumours, 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. And, the possibility for controlling matter on the femtosecond timescale – one day we may direct chemical reactions into specific or new products.

I now come to the epilogue of this lecture. I have tried through the history of one phenomenon, that of light, to show the power of scientific research that Rajiv Gandhi spoke about. A power that affects life itself; it helps us understand our origin as a species, and aids us in shaping the future. In this context, I am concerned about the recent report in *Nature* of London showing India's fall in its scientific research publication rate – in the past twenty years the number of scientific papers has fallen from about 15,000 to 12,000, while China has increased its output from 1000 to 21,000; South Korea's increase in output over the same period is similarly impressive. It is through science and science education that India can maintain its democracy and continue on the road to prosperity. Decades ago Nehru said the following: 'Who indeed could afford to ignore science today? At every turn we have to seek its aid . . . . The future belongs to science and to those who make friends with science'.

From the story I told today, perhaps several lessons may be drawn. First, in curiosity-driven research we really do not know what we shall discover, but in the process of searching, new concepts and new technologies may be developed, some of which will change our world. Science cannot be 'managed', but instead it requires a nurturing and supportive milieu – if provided, success is certain! Secondly, basic research is the foundation for technological advances; together with input from society they form the real triangle for progress. Cloning is a good example – it began as research in many laboratories, then it transformed into a new technology, and now society must address its ethical, moral, and religious dimensions.

The third point to make is the relevance of science to globalization. Science is international, and success in technology depends on research from the entire world community – the evidence for internationalization is clear in the story presented here, as the contributions made were from all around the globe. Globalization will be more effective and prosperity more widespread and fruitful, if science and technology become basic in the platform of national policy. Finally, science education: a culture of science beginning in primary schools is absolutely essential for the progress of society and for the enlightenment of the mind. It encourages the rational approach to the world, the mentality that seeks to question, to explore, and to participate in team efforts. Moreover, science education is at the core of our peaceful coexistence, as pointed out by C. N. R. Rao in his presentation at the Pontifical Academy.

With proper support and independence, I believe that science (and faith) will continue to provide humanity with light, liberty and learning. But science has to go beyond research and development and must become part of our global education in this modern world. The 'haves' must help and involve the 'have-nots' to alleviate poverty and illiteracy and move toward progress. Scientists are in a position to contribute to this earth-saving cause as they do well in their own disciplines, which promote human progress. No words can describe this feeling than those of Rajiv Gandhi: 'As scientists, you have the power to show us the way. You are not only men and women of science, you are citizens of the human race endowed with unique qualities. You are able to understand the physical world better than others. You have the means to transform it. You owe it to mankind that this special gift is used in the service of peace'.

Indeed when we think of peace we must think of Mahatma Gandhi, who showed the best in the human soul. In Stockholm last December (2001), at the celebration of the centenary of the Nobel prizes, I learned that the Committee for the Peace Prize had intended to give the Nobel Prize for Peace to Mahatma Gandhi in 1948, but he was assassinated and no prize was awarded that year. Had he lived one more year he would have received the Peace Prize. (My advice to those deserving ones who are still waiting is to live long enough!)

Mahatma Gandhi's message in life was tolerance and his words still echo in the world today. On the morning of 13 January 1948, this remarkable Indian leader and world peacemaker commenced his last fast, a life-threatening abstinence to encourage India on the path of peaceful coexistence and cooperation among Hindus, Sikhs and Muslims. Just before he broke his fast, the following Hindu verse was read:

Lead me from untruth to truth
From death to immortality
From darkness to light.

Gandhi's light is as powerful for the spirit as nature's light is for life.

I would like to close by reminding citizens of the world of the noble cause that Rajiv Gandhi wished for humanity – the building of (scientific) pyramids in the service of peace!

Received 25 November 2002; accepted 28 November 2002