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METAPHORS OF PHYSICS

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Our conversation is "peppered" with metaphors. I start deliberately with one to emphasize that metaphors occur commonly. While everyone accepts readily that they do so in our language, art, and especially poetry, they are just as common and important in the sciences even if less widely recognized.

I will consider a few metaphors, all very simple and already familiar in ordinary language as powerful metaphors. For instance, the pendulum, and its swing from one extreme to another, is often invoked in social or economic contexts, just as is the two-faced quality of a coin. But, in physics, we see even further elements in them. In saying "Ah ha, that is just the pendulum", when we encounter a physical situation or a mathematical equation with no strings or bobs involved, all kinds of other implications and consequences follow that add further richness to these metaphors as seen by a physicist.

Let us start with the simplest, "**dimension**". The original meaning and usage stems, of course, from the fact that we live in a three-dimensional world of length, breadth, and height. All are linear dimensions. Any length, distance, etc, whether an inch, a cm, a mile, or a light-year, is a [L], the notation of square brackets to express the essence, that these are all lengths in dimension, however we choose to measure them and whatever size they are. Equally, any area, whether of a surface on a screen or on the surface of our globe, is formed out of two perpendicular lengths and is a $[L]^2$: square feet, square miles, etc. Finally, any volume, whether of a rectangular box or a sphere, requires three independent lengths, and is $[L]^3$: cm^3, cubic feet, etc.

Already at this simple level, some important conclusions follow. As an example, deer, whether chital or blackbuck, are more slender looking than an elephant. The elephant is of course bigger and its legs will necessarily be bigger but, relatively speaking, they are more so, making for a stockier appearance. Dimensional consideration offers a reason. Most of the bulk of the animals, whether deer or elephant, is in the torso and head, but this weight has to be supported by the four columns of the legs. The weight, proportional to the volume, is borne on the area of these columns on the ground. Given the different scaling of areas and volumes, the diameter of the leg has to increase proportionately faster, like the 3/2 power, in going from the smaller animal to the larger. This is why larger animals are necessarily less slender looking. Other aspects of biological structures having to do with nutrient absorption, whether of food through digestive tracts or oxygen absorption in the lungs, or heat loss, again something that happens from the surface whereas the overall metabolism pertains to the entire volume of the body, can be similarly understood on the basis of the surface/volume ratio.

The next metaphor, the **simple pendulum,** a length of string with a bob, is perhaps the most important metaphor of physics. At least since Galileo, it has afforded a ready and accurate measurement of time. Indeed, extending our metaphor of dimension to include not just length but also time as an independent "dimension", it is easy to see that the time period of the pendulum can only be given by the length l of the pendulum and g, the acceleration due to gravity, the force responsible for its swinging. An acceleration is the rate of change of a speed, which itself is the rate at which a distance changes, so that physicists render the dimensions of acceleration as $[L]/[T]^2$. To make a time out of this takes, therefore, dividing the length l by g and taking a square root. That's all. We do not need Newton's equations or any further physics knowledge, just a consideration of dimensions. Given Earth's gravity g as about 10 m/s^2, a 1 m pendulum has a half-period of 1 second. Immediately, one can connect this to something which at first looks like it has nothing to do with pendulums, strings and bobs. Our legs, ~1m long, swing just like a pendulum. Since our stride is also about 1 m, and it is taken in 1 s, our walking speed is 1 m/s. With 3600 s in an hour, that translates to about 2 mph, about right as an estimate of our typical walking speed.

The pendulum's motion, called simple harmonic motion, is one of the most important in physics. There are many examples of simple harmonic motion, all metaphorically "the pendulum". In molecular vibrations, such as in the CO_2 molecule, it is the quantum motion of electrons and nuclei. In electromagnetic radiation, including the visible light we observe, there are no concrete material particles, marbles or bobs, just electric and magnetic fields which execute simple harmonic motion. But, to a physicist, they are all "just a pendulum". Turning next to two-dimensional motion, still of a pendulum, it can swing either east-west or north-south. Combining the two motions, there are two extreme options. Either the two are in step, the maximum east and north displacements at the same instant, and similarly the maximum west and south. This means a simple one-dimensional pendulum motion as before, but now in the NE-SW axis. Such a "**45^0 axes**" is itself a metaphor physicists often use and I will come back to this later. But, an alternative way of combining the two motions is to have them exactly out of step, the x motion being at zero when the y motion is at its extremes, and vice versa. Now, the pendulum's bob is not moving in a straight line but rather in a circle. This is called a conical pendulum. Instead of two linear motions in x and y, this is better viewed in what we call **circular coordinates**, again a recurring theme in physics and one I will return to. The link between one-dimensional harmonic motion in a line and two-dimensional uniform motion in a circle has applied importance as well, the up and down motion of the pistons in our cars converted to circular spinning of the wheels.

Turning to **waves**, we are familiar with waves on water and on a string. They serve as metaphors also for the electromagnetic waves that constitute visible light or radio waves, and Einstein's theory predicts similar waves of gravitation. "Standing" waves on a string or in air columns of flutes are the basis of all our music. The Schroedinger wave equation, which replaced Newton's equations of classical mechanics, describes waves albeit of abstract complex quantities. All of quantum physics has to do with these waves. Nowadays, string theory, as a possible theory of the fundamental entities of physics, considers them not as point-like particles of some mass but rather tiny strings, and rests on the same metaphor.

A metaphor of a different kind is built on an idea which I call "**adding a dimension**". To add a dimension may at first look like complicating matters but it often simplifies the problem. Recall the connection between one-dimensional simple harmonic motion and uniform circular motion. A more complicated motion with varying amplitude in one dimension simplifies by adjoining another dimension and seeing it as a uniform circular motion, all the complicated dynamics of the one-dimensional motion laid at the door of projecting down to that dimension. This is a very powerful metaphor in itself. Most people have heard that Einstein, in combining the three space dimensions with the fourth one of time into a single space-time, showed how this makes for a more natural, and powerful, description of physics than what existed since Newton. There are many physics examples of the theme of adding dimensions to simplify matters.

I turn to a different metaphor, the **coin**. Again, this is already a familiar metaphor of ordinary usage but has added elements in physics. An early one is in the understanding of magnetism, that it has its origin in electric currents, or a charge moving in a loop. Every loop, like a coin, is two-sided, and so are all magnets as pairs of north-south poles. Today, the coin metaphor occurs in an intimate way in the emerging field of quantum computing. Just as in a coin or a switch, which have two values, heads/tails, up/down or on/off, in quantum physics too there are systems with only two energy levels. What is significant about quantum systems is that they can also be in what is called a superposition of the two possibilities even though, whenever observed, only one of them is seen. An analogy is the best way to describe this, in terms of the metaphor of a sphere which is called the Bloch sphere after one of the original discoverers of nuclear magnetic resonance phenomena. It is as if the observation of such a quantum system always gives one of the two poles on a globe but the system itself can explore the entire vast surface of the sphere, not just two points. This is why, a quantum computer, if we ever build one, will have incredible memory and power. Unlike a classical bit/switch, with just two values, each "qubit" has an enormous (infinite) number of values it can access.

My next metaphor is of a **saddle**, whether of horses and cowboys or on mountains. In a mountainous region, we all know that saddles play a key role in going from one valley into another, and the Khyber and other passes have played an important role in history. Interestingly, saddles also play a key role in chemical reactions. Now, we are not talking of topography but again of quantum systems, and the same saddle metaphor has increasingly been recognized, so much so that we talk of what are called transition states that reside in saddles of potential surfaces and mediate chemical transformation. My own research in atomic structure, on the dynamics of two electrons in an atom such as helium, has exploited the conjunction of several of these metaphors. Though far removed from horses, cowboys and mountains, the potentials (equivalent to forces) seen by the electrons has a saddle. Exact equality of the two electrons' distances from the nucleus corresponds to being at the centre of the saddle, any departure from that equality getting magnified. The equality of distances is "the 45^o line" metaphor we encountered earlier, and plays a crucial role in doubly-excited states of atoms.

A very important metaphor is that of **symmetry**, again familiar in its ordinary meaning and usage. We have an intuitive feel for the bilateral symmetry of our own bodies or other symmetries of flowers, leaves and snowflakes. You envisage some change, transformation, whether reflection or rotation through some angle, but global aspects of the objects do not change, "remain invariant". This has become a very powerful metaphor throughout physics. As an example, for many purposes of nuclear physics, a proton and neutron behave similarly. This constitutes a symmetry and from it follow profound consequences. So much so, that all our fundamental theories of physics today start with identifying a symmetry and then associate an interaction or force with it. We also discuss what is called super-symmetry. And string theory, already mentioned, also builds on such ideas. Symmetry can also be inexact, just as in Nature, sometimes slightly "broken", at other times more drastically, but the idea itself of symmetry retains usefulness.

Let me summarize. We have looked at a few metaphors in their rendering in physics. There are many more, and every physicist will be able to make his own favourite list. I have selected some like the pendulum which perhaps will be in on everyone's list and some others like 45^0 axes, adding a dimension, and saddles because they have occurred in my own research work. Each metaphor is fairly simple in its first appearance and familiar even to a layman. What is remarkable about our subject of physics is the sweep of these metaphors across the whole field and over the several centuries of our subject, that phenomena which at first sight have nothing in common are, nevertheless, just the same in essence. There may be no strings and bobs, it may be a quantum motion of electrons or atoms, but the physics and mathematics are "just the pendulum's".

We may speculate on why this is so successful, that a few simple metaphors explain and account for so many disparate systems and phenomena. Ultimately, the explanation may lie outside of physics, in our biology, perhaps neurobiology, that it has to do with pattern recognition and how we think. As biological creatures shaped by evolution, recognizing patterns, whether in finding food or avoiding predators and other dangers, were most likely useful and of evolutionary advantage, even critical in shaping us. And those same small set of principles or metaphors we continue to use whether in quantum systems or ten-dimensional string theories, far removed from our immmediate experience.

Whatever the explanation, metaphors play as much of a role in physics, or science more broadly, as they do for our colleagues in the humanities, art and poetry. And this is what this lecture has attempted to convey.

Recent HONOURS to ALUMNI

T. Padmanabhan: *Padma Shri on January 26th, 2007*
D.P. Roy: *Satyendranath Bose Medal (2007) of INSA; (currently DAE Raja Ramanna Fellow at HBCSE)*
Govind Swarup: *Grote Reber Medal for lifetime achievement in radio astronomy*

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A Century of the Quantum

by

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Public Lecture on February 28th 2007, National Science Day, at Homi Bhabha Auditorium, Tata Institute of Fundamental Research, Mumbai.

1. Before the Quantum : The World of classical Physics

Before the introduction of the quantum in 1900 by Max Planck, it was commonly believed that classical physics provides a complete description of all the physical phenomenon. The main pillars of classical physics were (i) Newtonian dynamics (1687); (ii) Maxwell – Faraday electrodynamics (1864) and (iii) thermodynamics. The two basic entities were matter, consisting of mass points obeying Newtonian laws of motion and electromagnetic fields, describing electric, magnetic and optical phenomenon which obeyed Maxwell's equations. Matter was thus particle like and light, identified with electromagnetic waves, was wave like. Matter and fields carried out their play in the fixed arena of space and time. Further, refinements in the concept of space, time and gravitation were necessary and were given by Einstein's theories of relativity (1905, 1915). These provide a capstone to the beautiful edifice of classical physics.

Classical physics describes the world as it is i.e. its ontology is that of a "Realism". Both matter and radiation obey deterministic laws obeying causality. Probability has no fundamental role but can be used to discuss situations with incomplete information and/or those dealing with complex systems. Both the system, under observation, and the measuring apparatus are described by the same physics. It thus provides a unitary description, which is internally consistent and complete. It is thus an immensely satisfying description. Unfortunately, it fails to describe the world of atoms and radiation and their interaction i.e. the micro world, as opposed to world of larger scale phenomenon i.e. the macro world. It is here that the introduction of the quantum concepts is necessary.

2 Introducing the Quantum : The Heroic Periods of Old Quantum Theory (1900 – 1925)

Quantum Theory has been the most revolutionary conceptual development in the twentieth century. It's origin are in the problem of black body radiation.

Kirchhoff (1869) had shown, using thermodynamics, that the emissivity – absorptivity ratio for thermal radiation of a substance is an universal function depending only on the temperature T of the body and the wavelength of the thermal radiation, and is given by the emissivity of a black body. Planck proposed an empirical expression for the law of black body radiation on October 19, 1900 which fitted the precision data perfectly. It also reduced to earlier proposed Wien's radiation law for small T values, and to Rayleigh-Jeans law for large T values, where they were giving a good fit to the data.

Planck gave a formal derivation of Planck's law on December 14, 1900 to German Physical Society. He used a simple model of the matter, i.e. a collection of Hertzian Oscillators, in view of the universality of the black body radiation. Classically such an Oscillator could have an arbitrary amount of energy. In order to derive his law, Planck however had to assume an Oscillator of frequency f could have energy only in unit of integral multiples of a quantum of energy equal to hf. The h is now called Planck's constant. Planck, at first, regarded this assumption as a purely formal one.

The first person to realize that a definite break has been reached now with classical physics was Einstein. He showed that classical physics lead to the Rayleigh Jean's Law and not to the Planck's Law. The quantum revolution had begun. He proposed the light quantum (photons) hypothesis in 1905. He looked for the evidence for it in various processes involving generation and transformation of light. These included blackbody radiation, photoelectric effect among others. Einstein's photoelectric equation was fully verified by Millikan by 1915, who was an unbeliever in the photon hypothesis. Compton effect (1923) fully established it. The behavior of the radiation was thus quite puzzling. Some times it behaved as waves and sometimes as particles. Einstein is also the first one to apply it to the matter when he discussed specific heat of solids in 1907.

The third founding father of the old quantum theory was Niels Bohr, who in 1913 used quantum ideas to understand structure and spectra of atoms and molecules. He used Rutherford's nuclear model for atoms. He decreed that atomic system exist in only states of fixed energies. The radiation is emitted by them only when the systems makes quantum jump between two different energy states and has a frequency equal to energy difference between them divided by Plank's constant. Using Keplerian orbits for Hydrogen atom and quantizing the electron orbit angular momentum he explained its' Balmer spectrum lines as well as obtained an expression for Rydberg constant in terms of fundamental quantities. This led to prediction of Lyman and Paschen Series of spectral lines for Hydrogen, Pickering lines for singly ionized Helium. He also noted the correspondence between classical orbit frequency and quantum emission frequency for larger orbits. Bohr's theory was useful in understanding the periodic classification of atoms, Moseley work on X-ray spectra and qualitatively more complex atomic and molecular spectra. On precise quantitative level it however was not able to deal with Helium and singly ionized Hydrogen molecule.

The last great conceptual advance in old quantum theory was due to S.N. Bose who laid the foundations of quantum statistics in 1924 by treating blackbody radiation in a novel way. Einstein extended this approach to material particles. All integral spin particles, now known as Bosons, obey this quantum statistics.

The heroic period of old quantum theory was now drawing to a close.

3. Discovery of Quantum mechanics (1925 – 1927)

The correct mathematical formulation of the Quantum mechanics was achieved during the short, but an intensely creative period 1925-1927 in a number of versions. The first of these was 'Matrix mechanics' given by W. Heisenberg. While working with Kramers in 1924-25 on dispersion theory he found "Old quantum theory" to be a tight rope walking. One uses classical concepts, which one knows are not really valid in atomic domain, carefully and somehow marry them to quantization condition. He felt need of a new mechanics, which would replace classical mechanics, strongly.

He introduced, guided by Einstein's insistence on observables in special theory of relativity, two indexed quantities, where indices referred to the initial and final energy levels, for each observable such as electron position. It was later pointed out by Max Born that these quantities were matrices. In June 1925, while recovering from hay fever at the island by Helgoland, Heisenberg worked out the commutation rule of position and momentum variables. The matrix mechanics was soon developed extensively by Heisenberg, Born and Jordan.

Louis de Broglie, in 1924, put forward the suggestion that not only light has wave and particles aspects but matter should exhibit the same behavior. Einstein's in 1925, on calculating number-fluctuations in a Bose-Einstein gas of atoms also found a contributions which was wavelike, apart from the expected particle-like one. He thought the wavelike part was due to de-Broglie waves. Schrődinger was drawn to de Broglie's thesis in view of his interest in Bose-Einstein statistics. E. Schrődinger then went on to write the wave equation for the de-Broglie wave in December, 1925, now called "Schrődinger Equation". The energy levels of various systems were seen to be eigenvalues of this equation. This was the second formulation known as "Wave Mechanics". Incidently, the famous comment of Dirac that all the chemistry and most of physics is covered by this equation is about the Schrodinger equation and not about the Dirac equation.

The equivalence between matrix mechanics and wave mechanics was established by March 1926 by Schrődinger himself and by Eckart.

Dirac soon afterwards gave another formulation in terms of his q-numbers and the correspondence between classical Poisson Brackets and quantum commutators between position and momentum variables.

The Nobel Prize was awarded to Heisenberg in 1932 and to Schrődinger and Dirac in 1933 for these discoveries.

4. The World of Quantum mechanics

Once the mathematical formalism of the quantum mechanics was in place the great gold rush of applying it to the various physical phenomenon to understand them began and has continued ever since. Beginning with atomic and molecular physics and chemistry it has been successfully applied to condensed matter physics, molecular physics and high energy physics. It has been applied to from white dwarf stars to the creation of the universe. Whenever the calculations can be carried through they have yielded extremely accurate predications. The predicted magnetic moment of the electron agrees with experimental results to two parts in a thousand billion. There is no known instance of its failure anywhere.

In contrast the interpretation of the quantum formalism has been a matter of intense debate since it's discovery. The quantum phenomena, such as double slit experiment are so weird that no space-time visualization of what is happening is possible. The quantum theory of measurement is also very problematic. The quantum systems are in general is a state of linear-superposition of states having different eigen-values for any physical observable. But on measuring the observable it is found in only one of these states. How does that happen? While Schrődinger equation has deterministic evolution, we can only predict probabilities for observing any particular eign value.

During the early years, the so called "Copenhagen interpretation" of quantum mechanics was worked out Bohr and Heisenberg and others. It held sway as the dominant interpretation for a very long time. According to it the wave function provided a complete description of an individual system and not only a statistical description of an ensemble of systems. Einstein, Schrodinger, de Broglie and some other however did not subscribe to this interpretation. The celebrated debates between Einstein and Bohr at various Solvay conferences dealt with various possibilities of violating of Heisenberg uncertainty relations. This was not found possible. In 1935, Einstein – Podolsky – Rosen discovered some very puzzling non-local correlations in two particle systems, now called entanglement, in quantum mechanics which hinted at its incompleteness if Einstein locality was a feature of nature.

Beginning with work on John Bell, in 1966, the revival of debates about the interpretation took place and many other interpretations such as Bohm's casual, Everett's many world, etc., began to be discussed more freely. Bell's work made it possible to experimentally discuss aspects of nature such as Einstein locality. Philosophy thus entered the laboratory. Newer ways of looking at quantum mechanics such as "Consistent history approach" also emerged. Even more surprisingly, beginning in 1984, some of these debates on foundations of quantum mechanics have spawned a number of new quantum technologies, such as quantum cryptography, quantum teleportation and possibly quantum computing.

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Computing: 50 Years On

by

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TIFR Alumni Association Public Lecture (6th JRD Tata Memorial Lecture) on 27 July 2007 at the Homi Bhabha Auditorium

Introduction

We may each remember a year for different things: some personal, some related to our work and interests and some for the unusual events that took place. 1957 is probably like any other year in this respect. For many scientists, the launch of the first Sputnik from Baikonur in the then-USSR will be remembered as the event which transformed the race to space and was the stimulus for the man-on-the-moon program that followed in the United States. Physicists may remember the year for the award of the Nobel Prize to Yann Chen Ning and Lee Tsung-Dao, both from China and working respectively at the Institute of Advanced Study, Princeton, and Columbia, for their work on parity laws. We in India may recall that it marked the first full year of operation of the Apsara nuclear reactor at Trombay. And, chess-lovers will certainly remember the year for the remarkable feat by Bobby Fischer in becoming the US chess champion at the age of 14!

There were landmarks in computing in 1957. By that time, around 1000 computers had been sold worldwide (none of them in India) and new computer series (with solid-state technology) were announced by the big manufacturers such as IBM, Univac, NCR and Siemens. Development of the integrated circuit was nearing completion in the laboratories of Jack Kilby at Texas Instruments and Robert Noyce at Fairchild. The Fortran programming language was formally published by a team led by John Backus at IBM, marking the start of a great era of programming language development. And Simon, Newell and Shaw devised their General Purpose Solver (GPS) which used *Means-Ends* analysis to solve some classical problems and joined John McCarthy's pioneering work as another milestone in the development of artificial intelligence.

Computing was not cheap in those days and strenuous efforts went to making the most effective use of the available computers. Large computers cost in the region of $500,000 and were beyond the reach of most universities, even in the United States. It was only when a few well-known US universities were gifted with Univac-1 machines that they were able to venture into large-scale computing. Among them was the University of Pennsylvania, famous for the construction of ENIAC (1943-46; the first large-scale computer, used extensively by the US Army) and EDVAC (1949; the first stored program computer in the United States). The Univac-1 was a decimal machine made with 1000 vacuum tubes and 1000 6-bit words of acoustic delay line storage – a powerful machine for its time but with rapidly aging technology.

TIFRAC

This was the context in which India took the first steps towards digital computing with the design and construction of the TIFR *A*utomatic *C*alculator, TIFRAC. A pilot study from 1954-56 was used to try out different electronic designs using Indian components and the team, led by R. Narasimhan, was ready to embark on building a large digital computer. When completed in 1960, TIFRAC had 2700 vacuum tubes, 1700 germanium diodes and, with a great deal of foresight, 2048 words of the then relatively new ferrite core memory. TIFRAC also resulted in the first attempts at system programming in India. In terms of hardware technology, TIFRAC was ahead of the Univac-1.

The design and construction of TIFRAC was a remarkable feat for Indian electronics engineering. It also provided an introduction to computing for many Indian scientists. Publications from that period show just how much the calculations made possible through the use of TIFRAC contributed to the development of science in TIFR (e.g. S.K. Bhattacharya, S.K. Mitra, Beta-Gamma directional correlation in Eu^{154}, *Phys. Rev*. **126**, 1154-1159, 1962) and in other Indian institutions like Benaras Hindu University (M.L. Rustgi, S.N. Mukherjee, Octupole deformation in even-even medium mass nuclei, *Phys. Rev.* **131**, 2615-2616, 1963).

So by 1960, thanks to TIFRAC, Indian scientists were just a few years behind their counterparts in leading institutions in other countries in terms of access to scientific computing. Of course, TIFRAC had to serve the whole of the small but widely dispersed Indian scientific community, while scientists in the West and Japan had computing facilities nearer to hand.

Computing Without Computers?

Algorithms have been of mathematical interest from at least the time of the Greeks (e.g. Euclid's algorithm for finding the Greatest Common Divisor of a set of numbers). And interest in complexity can be found from the 19th Century, for example Lamé's Theorem (1845) proving an upper bound for the number of steps taken by Euclid's algorithm. An honours list of mathematicians had looked at problems in complexity, from Cantor and Hilbert to Post, Church, and Gödel.

Yet, to create the fundamental basis of computer science before the existence of any computers took a truly remarkable man, Alan Turing. A lot of Turing's early work can be traced back to the major mathematical problems of the time. However, his abstract constructions of computing machines were entirely unique. Turing invented the concept of the universal computing machine, defined computability, proved basic decidability results and worked on a wide range of areas such as formal program verification, artificial intelligence, chess programs, neural nets and (what he is often best remembered for in the public imagination) statistical methods for code breaking.

(Turing led the way in other areas too: he was a world-class long distance runner and completed a full marathon just 11 seconds slower than the Olympic winner of the time.)

It is for his work on what we now call Turing machines that he is best remembered. A Turing machine is the simplest possible abstract computation device and Turing showed that any problem that is computable is solvable on it. So deciding whether a problem is computable or not depends on whether there is an algorithm for a Turing machine to solve the problem. Not all problems can be so simply categorized: there are some problems that are undecidable. For example, given a program and an input to the program, will the program eventually stop when it is given that input? This *Halting Problem* is a classical example of an undecidable problem.

Given the breadth of his abilities and interests, it is surprising that there actually were areas in which Turing did *not* make contributions. It appears that he did not consider the speed of execution of a Turing machine, or that an infinitely fast Turing machine could 'solve' the Halting Problem. He also did not make a breakthrough in complexity theory, despite the long interest of mathematicians in complexity.

Computing in the 1960's

Across the developed world, computing picked up momentum in the 1960's. IBM announced the first large series of computers, the 360 series, intended to span all applications, from small business requirements to large-scale scientific computing. The machines initially used 'hybrid' logic modules but by the mid-1960's all models used integrated circuits. The IBM 360 Series found widespread commercial and educational use, especially because there was close integration between the system and the wide range of application software, and backed by the largest disc memories of the time.

Similar but smaller series of computers were being manufactured by other companies in the US and Europe. But it was also the period when new kinds of computing systems were being introduced by companies like Digital Equipment Corporation: these included the mini-computer, for use by a single programmer or for a single application, and time-sharing systems that allowed tens and sometimes hundreds of people to access a computer system simultaneously. There was talk of computing being provided as a utility, in the same way that power and water were. There was even a suggestion (fortunately ignored) that countries like India could avoid buying and maintaining expensive computers and rely entirely on using telecommunication links to access large computers installed in the United States!

Work had started on the design of the hardware and the software for large parallel computers, notably at the University of Illinois where Illiac IV was being developed. (Illiac IV was later to achieve a speed of 200 million operations a second, far beyond the capabilities of the fastest machines of the time.)

In India …

Commercial computing started in India in the early 1960's when an IBM 1401 was installed at the new Backbay office of Esso Standard Eastern. This was the first of a set of similar computers installed in Indian companies over the next 10-12 years.

By 1962, the first Indian transistorized computer, ISUJU, was designed and built by the Indian Statistical Institute and Jadavpur University. Shortly after that, large scientific computers were installed: a CDC 3600 at TIFR and, in 1967, an IBM 7044 at the Indian Institute of Technology in Kanpur which took over from the earlier IBM 1620 (all with discrete components, not integrated circuits). In 1968, the first Indian software and management consultancy was created: Tata Consultancy Services can rightly claim that from the time of their creation they have remained the largest Indian software consultancy.

Within a few years, it became clear that the design and construction of modern computers had moved beyond the capabilities of universities and research institutes. There were still a few examples of special-purpose computers being built (the TIFR Oldap was an example) but those activities slowly died out.

Computer Science in the 1960's

This was an enormously formative time for computer science throughout the world. After Turing's foundational work in the 1930's, the pressures of the war had moved attention towards the design and use of computers for solving large numerical problems, especially because of the demands from the military and the funding available for such applications.

By the 1960's, a great deal of attention was directed towards artificial intelligence, once again because of military interest. Areas like automated language translation (predictably, given the preoccupations of the Cold War, from Russian to English), automated speech recognition and war-gaming gained prominence. Considerable effort went into these areas but more theoretical work also prospered, especially in automated theorem proving. Programs to play chess occupied the middle ground and Mikhail Botvinnik, the 1963 World champion, predicted that "a Russian computer chess program will beat the world champion" (presumably not him).

But this trend began to change with new foundational work on the theory of algorithms and complexity theory. Turing's work had showed how to determine which problems were solvable and which were not, which were decidable, and which were not. There remained the basic question of whether all computable problems can be solved equally easily. This was the question addressed by Hartmanis and Stearns in their now-famous paper of 1965 which built on earlier work by Yamada and by Cobham. They were able to define an abstract quantification of the time and space of a computation, e.g. as the number of steps needed by a Turing machine to solve the problem and the amount of storage needed. Their work laid the foundation for modern complexity theory†.

For computer science, the work of Hartmanis and Stearns led to the definition of the classes of P and NP problems and the still incomplete classification of the polynomial hierarchy. The work was key to defining the fundamental problem of whether P=NP, the first solution for which will receive a prize of $1 million from the Clay Mathematics Institute.

Program verification also had its modern roots in the 1960's through the work of Floyd (1967) who showed how to prove properties of programs and Hoare (1969) who defined an axiomatic basis for proving program properties. Independently, Dijkstra was leading efforts for formal program derivation, going from the desired goals to the programs that would achieve those goals. (Dijkstra described himself as a 'mathematical engineer'). The later work of Dahl, Dijkstra and Hoare on what was called 'structured programming' marked the start of interest in formal programming methodology which has since influenced programming substantially.

In India …

It took many years before the new face of computer science was reflected in work done in India. There was the long-held belief that the only 'fundamental' research in computer science was in selected areas of artificial intelligence and that the main scientific applications were to solve ever more complex numerical problems. Anything else was ignored and the enormously exciting developments of the time in computer science received no attention.

Whatever be the reasons for this skewed perception, there is no argument about the severely debilitating effect of the lack of computers in India. Until the mid-1970's, there were fewer than 100 computers in the whole country and most of them were used for commercial applications in companies. Except in very few institutions, students learnt programming as a paper-and-pencil exercise and only later, and very briefly, were they able to actually execute a program through a few batch runs on a computer. How could modern computer science have grown in this inhospitable environment? It was like doing natural science without any basic experimental facilities!

The result was that the years from 1960-1975 were a dull period for computer science in India. Today, it is hard to locate any significant computer science publications from work done in India at that time.

1970's and beyond in India

By the mid-1970's, the availability of computers in India improved. At the same time, work started in some new areas as more computer scientists returned to India. Groups grew at TIFR, the Indian Institute of Science, Bangalore, the five Indian Institutes of Technology, Jadavpur University, and the Birla Institute of Technology and Science, for example. A large group with interest in programming formed at the National Centre for Software Development and Computing Techniques (NCSDCT) at TIFR.

The manufacture of computers started in India. The Electronics Corporation of India started producing, albeit in very small numbers, mini-computer class machines. Commercial computers were assembled by IBM in Mumbai and ICL in Pune. These were all machines that needed to be installed in dedicated, air-conditioned facilities, out of the reach of most of the people who wrote programs.

One major limiting constraint to growing computer technology was the lack of availability of components from Indian sources. Integrated circuits were not manufactured in India (a situation that has not improved much even today) and imports of so-called high-technology components were fraught with difficulty and delay. This led to the questionable decision to limit computer design to what was possible using Indian components. While computing technology in the rest of the world moved on to faster and more compact medium-scale and large-scale integrated circuits, computers were designed and built in India using discrete components. Bucking technology, even if purporting to support nationalism, is always futile and, as the subsequent history showed, this case was no exception.

1980's and Onwards, in India and Elsewhere

There were two events that make the early 1980's memorable. The first was the launch of the Space Shuttle which promised to change the way near-space would be used for travel and scientific experiments, and possibly as a staging post for longer journeys. The second was a purely commercial event: the launch of the IBM PC.

There will be long debates about which event had a greater scientific impact and which affected more people. But it is hard to deny that the IBM PC, and the path this cleared for other manufacturers' PC's to be sold worldwide, changed the way we all view computing. Even the World Wide Web, proposed by Tim Berners-Lee at CERN in 1989, would not have had such a fertile reception without the wide availability of computing at a personal, rather than an institutional level.

In an India that had been starved of computing facilities for so long, the arrival of the PC made computing much more widely accessible. Institutions were the first major buyers of PCs but they found often place on individual desks, rather than only in computer centres. It was much later, in the 1990's, that PCs started to find a home market in India, following the liberalization of the economy, the rapid growth in telecommunication access in cities and the fall in communication rates. Selling a PC to an individual was still hard but a PC with an Internet connection could offer promises that vendors were quick to exploit. Not coincidentally, this was also the time when Indian software companies started to grow very rapidly.

Computer science in India saw the start of a new era. The FST&TCS conferences started by NCSDCT in 1981 grew in importance and rose to become among the most significant theoretical computer science conferences outside the West. Publishers who were loath to publish the Proceedings of FST&TCS in its early years later vied for the publishing rights. Important text books were written by Indian computer scientists based in India and highly referenced publications started to make their appearance.

More research work was being done in different research groups and began to attract wider attention. Of this, undoubtedly the most important result was the discovery announced in 2002 on primality testing. It had long been suspected that primality testing was in P (and hence potentially of practical importance) but it needed the ingenious algorithm devised by Manindra Agrawal and two undergraduate students at the Indian Institute of Technology in Kanpur to prove this. The result was important enough to bring them high honours: the Clay Research Award (2002), the Fulkerson Prize (2006) and the Gödel Prize (2006).

But Indian computer science was (and still is) very small when compared to the burgeoning Indian computer industry. There were relatively few additions to the number of computer science departments that existed in the 1980's and very few new staff or students were added to any of them. In comparison, from small beginnings and with undiminished persistence, Indian companies had begun to make themselves known across the world and to demonstrate the effectiveness of outsourcing and off-shoring. If factorization remained out of reach of computer scientists, the Indian software industry had made factoring of IT services into a practical reality that could not be ignored.

Indian IT industry – 1980's onwards

The large Indian IT companies started their existence by forming alliances with major IT players and computer manufacturers, providing them and their customers with staff to meet their growing needs. But this was not seen as an end by any of them and at least one company invested in R&D. In 1981, Tata Consultancy Services created the Tata Research Development and Design Centre, the first R&D centre in the Indian software industry and today still the largest. Some companies chose to follow what they decided were the technology imperatives laid down by companies in the United States but others began to develop technology and build their own software tools to increase productivity.

For many years, outsourcing work was done by staff from Indian software companies working exclusively within the premises of the outsourcing company. That situation began to change by the late-1980s and work was moved to centres in India, each dedicated to a specific client. These overseas development centres, or ODCs, functioned as part of the outsourcing company in all respects but their location. The staff working there became familiar with the work ethos of the outsourcing company and worked in a computing environment that was identical to the one used in that company: the aim was to create a single team divided only by geography and time zone that would take turns in operating through long 15-20 hour working days.

Setting up an ODC marked a level of confidence that led to closer integration between the teams in different locations. Joint work became less a question of 'them' and 'us' and more about assigning responsibilities to the location where they would be carried out best. The work became more successful when the outsourcing companies became more mature in their practices and had a clear idea of how they wished to manage their IT development across the world. The ability to provide services for this kind of work was key to the success of the Indian industry and gave it a level of immunity from even the .COM failures. By 2002, just over a year after the .COM carnage among Silicon Valley companies, an Indian IT company quietly crossed $1 billion in revenues.

From the late 1990s, the Indian IT industry grew at a compounded annual rate of 28%; its share of the Indian GDP rose from 1.9% to 4.1% in 2004. By 2008, it is expected to contribute 7% to the Indian GDP and by 2010 the total revenues could reach $80-100 billion.

These are not small sums of money, and the applications that the Indian IT industry has been responsible for are by no means minor or trivial. Modern software systems represent some of the most complex artifacts ever produced and an increasing number of them now have their origins in India. When deservedly praising the achievements in other fields that we can see, we should not overlook the software that we cannot see but which makes possible the successes in fields as diverse as international financial services and intricate drug discovery systems.

The Indian IT industry has changed the whole nature of software development, from using single teams in one location to dividing work across teams in multiple locations bound together by a well-defined software process. This was a necessity for successful outsourcing work but the quality of what resulted is best assessed in terms of the growth of the companies. It is no accident that most of the highest certified IT companies in the world are in India.

Price of Success

The success of the Indian IT industry made it a magnet for employment. The demand it created led to an educational shift towards computing and today an increasing number of young people look for careers centred on IT. There has consequently been a big growth in IT-related educational courses but unfortunately this has not been matched by a growth in the number or quality of the teaching staff.

With almost no more research happening in computer science departments than a decade ago, very few research students and a worrying trend towards a further fall in educational standards, there is a great deal about computer science and engineering education that needs to be corrected. In this, the Indian IT industry needs to play a much larger and more active role. It is the major employer of these students and it will be the most affected if educational standards do not start to rise. The industry needs to work with a much larger research base than is available today: there are fewer PhD students in computer science in the whole of India than in an average university in the United States! Just as the energy companies of the 1970s began to worry about the depletion in natural sources of energy, Indian IT companies need to consider how they will continue to grow, and grow effectively, unless their sources of trained staff are augmented and the quality of education improved.

The demand from the Indian software industry has created an unfortunate bias in the spread of science and technology courses. Given the uncertainty of finding gainful employment in science and many branches of engineering, students have flocked towards computer science and IT courses. This is also not a trend that should continue. But rather than decrying the software industry despite its successes, the more important task is to find other areas of science and technology that can aspire for the same success.

But is it Science?

Computing has often been misunderstood by non-practitioners in India. In the early years, natural scientists treated it as another form of electronic instrumentation, as complex and as necessary as, say, an oscilloscope and merely another tool for scientific work. Software for commercial applications was derided as no more than electronic clerical work. That view has been heightened today because of the feeling that the indisputable success of the industry and the well-paid jobs it offers must represent a passing phase before an inevitable collapse. Yet, the industry continues to prosper, year after year …

Is computer science really a ‘science’? Is it a technology? Or it is engineering? These are valid questions because computing technology usually runs well ahead of computer science. But computing technology and computer science have complementary roles: the technology generates the ‘phenomena’ that are observed and studied, creates the need for new theory and provides the environment for validating theory. Computer science can also proceed independently, as Turing’s work showed, but thrives with a closer association with practice. Computer technology and science prosper when they work together and will wither if they are kept apart for too long.

A traditional science relies on observations of natural phenomena at different levels. Computer science is not a natural science in those terms but it is unquestionably a mathematical science. Like any science, it has theories and it makes predictions; but the phenomena it observes are from the world of technology. Computer science is related to information technology as closely as any science to its application technology. One should not be confused for the other and neither tells the whole story.

Finally …

The success of the Indian IT industry has set a challenge: can Indian computer science make as big an impact? This is not a frivolous question because unless industry and science are more closely matched in the future, they will both be confronted with barriers that could become insurmountable.

The successes of today suggest that a far better future awaits them both, provided the industry and its educational and research counterpart work as closely together as theory and practice in any science. There is a lot that both have to discover.

Acknowledgements

The occasion for this talk is the birthday of Mr. J.R.D. Tata on 29th July. His influence on Indian industry and Indian science was so outstanding and so large that it is hard to envisage where they would stand today without his discerning support at the early and critical periods of their existence. It is a great honour to be able to give this talk on such a notable occasion.

I would like to thank the TIFR Alumni Association for inviting me to give this talk and giving me the reason to collect my thoughts on computing in India over the last half century.

I have relied on a number of sources for the information I have presented here because the story starts long before I started my research career at TIFR and spans a far wider canvas than I have had the privilege to be part of. I have made liberal use of that wonderful and beguiling tool, hindsight, and it is possible that my account refers to information that was not easily available at the time the events took place.

Finally, I would like to thank former colleagues and present friends at TIFR, at Warwick University and at the Tata Research Development and Design Centre for all I have learnt from them over the years. Some of them were gracious enough to comment on earlier versions of this material. None of them is responsible for the views I have expressed or for any errors that remain in the text.

Remembering Prof. M.B. Kurup

Prof. M. Balakrishna Kurup shouldered the responsibility of the Dean of Natural Sciences Faculty (NSF) at Tata Institute of Fundamental Research (TIFR) in a distinguished manner over a period of four years from August 2002 to September 2006. He was also currently serving as the Chairman of the Committee for Pelletron Accelerator Facility and the LINAC Booster project, joint initiatives of TIFR and Bhabha Atomic Research Centre set in motion at the Colaba campus of the institute in early 1980s. Professor Kurup's research activities during the past 35 years spanned a wide range of fields, from condensed matter physics, atomic physics, nuclear physics to accelerator physics.

The School of Natural Sciences (SNS) at TIFR comprises the subjects of Physics and Astrophysics, and broad areas in Chemical and Biological Sciences. SNS is organised into seven distinct departments, namely, those of Theoretical Physics, Astronomy and Astrophysics, Atomic and Nuclear Physics, High Energy Physics, Condensed Matter and Materials Science, Chemical Sciences and Biological Sciences. Prof. M.B. Kurup rose to assume the apex position of Dean of this largest School of TIFR after three decades of high scientific achievements and dedicated service.

Balakrishna Kurup (Bala, to his friends) had been selected as a Visiting Member in the School of Physics of TIFR in 1972, soon after having secured a first rank in the M.Sc. degree in Physics at Sardar Patel University, Anand (Gujarat). Prior to it, he had earned his B.Sc. Degree with distinction from Kerala University. Bala completed the Graduate School course work at TIFR in 1974 and went on to register for the Ph.D. degree at University of Mumbai under the guidance of (late) Prof. B.V. Thosar, the then Head of Nuclear Spectroscopy Group. He had commenced his experimental work under the supervision of Prof. R.P. Sharma and Dr. K.G. Prasad, and chose to focus on research issues in condensed matter physics and materials science for his thesis. Bala was quick to gain mastery of a wide variety of seemingly different techniques of experimental nuclear physics and nuclear spectroscopy. He applied them skillfully to explore a wide variety of materials, and contributed to the understanding, via the microscopic nuclear hyperfine interactions, of the several contemporary physics problems, ranging from pristine issues of condensed matter in elemental solids, magnetic behaviour in rare earth intermetallics, transition metal alloys and ferrites, phase transitions in cholestric Liquid Crystals, study of ionic solids, like, alkali halides, exploration of materials, like, Uranium (U), Uranium oxide (UO_2) , etc.. Even as a Ph.D. student, Bala had gained recognition as an experimentalist, who was not only endowed with a multi-dimensional expertise in the laboratory based nuclear physics experiments and the in-situ beamline explorations using large accelerators, like, the Van-de-Graff machine at BARC, but also, had a broad vision of materials science, atomic physics and nuclear physics. The inter-disciplinary areas of nuclear and condensed matter physics that he explored, fully utilized the nuclear techniques, like the resonance absorption of gamma rays (Mossbauer Effect) , perturbed angular correlation, positron annihilation lifetimes, channeling of charged particles in single crystals to study effect of very tiny (less than one hundredth of a nanometer) displacements of atoms, etc.

Balakrishna Kurup was made a regular academic member at TIFR in 1977. Prior to it, he had already teamed up with Prof. R.P. Sharma and Dr. K.G. Prasad to commence building a low energy (400 KV) Heavy Ion accelerator capable of accelerating ions of any element (Hydrogen to Uranium). The commissioning of this state of the art indigenously built machine in 1974 greatly enhanced and widened the scope of hyperfine interaction studies at the institute and pushed them to the centre stage of their field internationally. The collaborations with the material scientists, particularly those interested in novel applications of semiconductors and magnetic materials, multiplied rapidly. Dr. Kurup went on to disseminate his noteworthy results in International Conferences abroad, visit and give lectures at well known Nuclear Physics Centres in Europe, like, Laboratorium Voor Algemene Natuurkunde, Groningen, F.O.M. Institute at Amsterdam, Centre for Nuclear Physics, Karlsruhe, Department of Physics at University of Padova, etc.

University of Bombay awarded the Ph.D. degree to M.B. Kurup in 1982. The decision to acquire a new Pelletron Accelerator for Heavy ions from a US Corporation had been set in motion by Department of Atomic Energy for TIFR and BARC scientists. Dr. M.B. Kurup was now asked by TIFR to get exposure to the futuristic next phase of the Pelletron accelerator, namely, the Superconducting Linear Accelerator (LINAC), at the State University of New York at Stonybrook, where the work on prototype Superconducting LINAC was underway. Dr. Kurup became a key member of the Stonybrook team which evented the first successful operation of their new LINAC machine in 1983. Dr. R.G. Pillay of TIFR was also subsequently asked to proceed for his Post-Doctoral work to the Stonybrook Laboratory, partly overlapping with the Post-Doctoral stay of Dr. Kurup there.

Dr. M.B. Kurup and Dr. R.G. Pillay along with Prof. H.G. Devare (TIFR), Dr. S. S. Kapoor (BARC) and other BARC and TIFR scientists laid the foundations of the development of first superconducting LINAC module in mid eighties in India. In conformity with the tradition of Department of Atomic Energy to develop high technology indigenously, the entire project, except the liquid helium liquefier, was conceived to be executed using in house infrastructure and Workshop facilities at TIFR and BARC. The heart of this project has been fabrication (machining, welding and electroplating with Lead) of OHFC copper cavity resonators to nano/meso-scale specifications, design and development of sophisticated cryogenics, cryo-transport systems, beam optic elements, rf electronics, control systems, etc. After several years of dedicated efforts by teams led by Prof. M.B. Kurup and Prof. R.G. Pillay, the first phase of this project involving three modules, each module comprising four quarter wave Lead plated superconducting cavities, and a superconducting buncher was successfully demonstrated in September, 2002 by boosting Si beam energy by 45 MeV.

While Prof. Kurup remained engaged in development of

Superconducting LINAC, the 400 KV machine that he had built earlier in his career also remained a work horse for him for nearly three decades for investigations of ion beam modification of materials as well as for atomic physics experiments like beam foil spectroscopy, X-ray emission at low energy. He along with Prof. K.G. Prasad and R.P. Sharma had established a strong group activity to employ the powerful technique of crystal channeling, where energetic projectiles are constrained to follow a restricted path inside the crystal along the symmetry axis/plane, for investigating a variety of physics problems. There were only a few groups worldwide who were working on this technique. Some examples are: energy loss of channeled charged particles, impact parameter dependence of M X-ray yield, properties of implanted materials. With the advent of Pelletron accelerator, he continued his extensive collaboration with Prof P.N. Tandon, Prof K.G. Prasad and L.C. Tribedi to study the various effects associated with inner shell processes in heavy ion atomic-collisions. Especially he contributed a major way in the X-ray studies of the highly charged ions in crystal-channeling as well as in ion-gas collisions. This collaboration produced several interesting results: such as ion-solid state effect on the radiative electron capture (REC) by bare ions (H-like or He-like) channeled through the crystal, a double peak-structure in the projectile x-rays for channeled ions. These were established via the study of the energy and the yields of the REC X-ray photons. In addition, at a later stage he was also involved actively in the experiments to study the so called saturation effect on the projectile K-shell excitation of He-like ions in collisions with gaseous targets. Prof. Kurup had plans to study channeling through Carbon nanotubes in the near future. In last few years he and Prof L.C. Tribedi had planned for up-gradation of the 400-kV ion implantation machine by including an ECR (electron cyclotron resonance) ion source on the high voltage deck. The entire work plan is in place and the initial work was started a couple of years back when the ECR source was installed to have initial testing and experiments. He had lots of interest towards the starting of ion-surface collision experiments with the upgraded machine.

Some other experiments with 400 KV accelerator that he had initiated included the study of effects of ion implantation on electrical and structural properties of nylon-6, where the modification of polymer chains due to radiation damage was demonstrated. He was involved in the measurement of lifetimes of several excited levels in CII and CIII, which are of astrophysical interest, using beam foil spectroscopy in the visible-UV region. In the last couple of years he had also commenced a program to study radiation induced damage to the DNA molecules, in collaboration with Prof. L. C. Padhy of Department of Biological Sciences.

His research interests in Nuclear Physics centered around probing the nuclear structure by measuring the lifetimes as a function of initial excitation energy of the compound nuclei in mass 40 region populated with 12C, 16O, 19F beams from the Pelletron accelerator. These ultra short lifetimes in the range 10-17s to 10-18s were measured using the crystal blocking technique, which is complimentary to channeling, with very thin single crystals of Silicon (developed at TIFR). At his suggestion time of flight discrimination method was used in conjunction with crystal blocking for separating reaction products.

The first set of research experiments conducted using the first phase of Superconducting LINAC machine in April-May 2003 got evented in international refereed journals. The second phase of the full Superconducting LINAC facility extending to the new beam hall, with multiple beam lines, continued in the Tenth Plan period (2002 - 07). The second phase is nearing completion now. In spite of numerous other responsibilities in recent years, Prof. Kurup remained enthusiastically attached to the LINAC project to which he had contributed significantly. His key contribution in the R&D efforts of the preparation of superconducting Lead surface of the RF cavities, the core part of the accelerator, would remain always remembered.

A quintessential characteristic of Prof. Kurup was his openness to new ideas and enthusiasm about getting into new ventures. His expertise in dealing with wide range of accelerators (KV to MV), associated technologies and instrumentation made his leadership of the Pelletron and LINAC project very valuable.

Tapan Nandi (Atomic Physics), Nandini Bhattacharya (Atomic Physics), Vandana Nanal (Nuclear Physics) received guidance from Professor Kurup for their Ph.D thesis at TIFR. He also remained for a long time the representative of TIFR on the Research Committee in Physics of the University of Mumbai.

He served on the Research Councils of many institutions in the country, including the prestigious DAE units, like, IGCAR, Kalpakkam.

- Arun Grover, Vandana Nanal. & Lokesh Tribedi

Remembering Prof. M.L. Mehta

Professor Madan Lal Mehta was born on December 24, 1932 in a small village Unthala in Rajasthan. His childhood years were spent in Relmagra near Udaipur, and nearby villages. Later his family moved to Udaipur, where he spent his adolescent years. Madan Lal obtained his M. Sc. Degree from the University of Rajasthan, and joined Tata Institute as a research Scholar in 1957, in the same batch as Professor C. S. Warke.

For his Ph. D., he worked with Prof. C. Bloch at Saclay. It was here that he started his work on random matrices, in collaboration with M. Gaudin. He obtained his Ph.D. from University of Paris in 1961, and was invited by Wigner to the Institute of Advanced Study in Princeton.

Here he wrote a series of very influential papers with F. J. Dyson. After his Ph. D., he returned to T.I.F.R., but resigned after a year, and moved to Delhi University, and from there back to Saclay, where he spent most of his professional career.

After retiring from Saclay, he returned to his native Udaipur with his Chinese wife Rani in January 2005. He was struggling with Parkinson's disease for some time. He died on December 10, 2006, after complaining of chest pain.

Madan Lal is known to physicists around the world for his work on random matrices. The general problem is to determine the probability distribution of eigenvalues of matrices whose elements are selected randomly from a prescribed probability distribution. Mehta and Gaudin in two papers in 1960 introduced the method of orthogonal polynomials to study this problem analytically, which has been one of the most important tools in the subsequent studies of this problem. First introduced to study energy levels of heavy nuclei, the subject of random matrix now finds application in many areas ranging from elementary particle physics to ecology. His text book "Random Matrices" has been very useful in introducing generations of students to this fascinating subject. The book is notable for its clarity of expression and precision in language.

Mehta was a colourful personality. He was very conscious of his Indian roots, but did not hesitate in deploring things here that he found superstitious, feudal, or hypocritical. For example, he loved Hindi, and angered many Indian friends who visited him in France by telling them that they discuss with him not in English, but in their own language Hindi, or in French. He knew several languages: Hindi, English, French, Chinese, Japanese and Russian. Once, in Paris, Shasanka Roy commented on his rather ill-fitting pants. He laughed and he said that he had stitched them himself! An account of his many adventures in many lands can be found in his memoirs "Pravasi Panchhi" (in Hindi, unpublished), a copy of which is kept in the TIFR library. I feel that it was a privilege to have known him. I still remember the kind hospitality he and his wife Rani extended to me, when I was an uninvited guest at his house in France for a few days, when my passport was stolen at the Paris airport, and I had to stay in Paris till a new passport could be arranged. With his death, we have lost a great physicist, and a great human being.

- Deepak Dhar

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