

Fun and joy of science: Learning from anomalies and discontinuities^{*,†}

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Research in a 'Zone of Comfort'

I have titled this article as 'Fun and joy of science: Learning from anomalies and discontinuities'. Why have I chosen this topic? I find that many of our scientists and engineers are generally comfortable in status quo. Most of us are happy with organized research. A problem is posed and a solution is found. We use all the known tools of science, theoretical and experimental; be they instrumental, which span an amazing range of length and time scales, or computational, whose power and reach are becoming mind-boggling. Invariably we develop models and theories and try to fit the experimental data or we do vice versa. When the models fit the experiments, we are all happy. The student is happy, since he can finish his Ph D thesis in time and perhaps seek a postdoctoral in that land of opportunity, namely United States of America. The guide is happy, since he feels here is one more of his contributions to the pool of scientific knowledge, and also because one more research publication is now under his belt. The referee of the paper is happy, since the theory or model fits the experiment; surely if there is a fit, both the theory and the experiment must be right! He does not have to stretch himself. The editor is happy too, since he is not publishing a paper, which is likely to raise controversies. So this is the happy zone, a comfort zone!

But what about those problems, which are not in the comfort zone? Those unresolved problems, which have been crying for answers for years, but are too risky to try. What about those observations, which look anomalous, since they go beyond what would be expected by common sense? What about those sudden discontinuities that appear on the horizon? When a theory or a model is developed, most points fit the line of prediction, but some data fall outside. Are these just experimental aberrations, or is there a deep message in them, which can open up a

new frontier? It is my feeling that many of us leave such things alone, like a fast rising cricket ball outside the off stump. We do know that trying to hit it can bring rich rewards but there is a danger of getting caught behind too! I am going to persuade you to believe that there are a lot of rewards in taking those risks and moving out of our comfort zones to solve problems that are challenging and risky at once.

I will cover diverse aspects of this issue. First, I will share some of our own joy and fun in working in this zone of discomfort. Can one organize funding of risky problems in science? I believe we can. Again I will share our own experience in doing it, first at the laboratory level, then at the CSIR level and then at the national level. I am also going to extend this to technological issues, just to show as to how an eye for anomalous observations has led to new discoveries and new technologies. From science and technology, I will move on to organizational issues, namely the issue of creating 'innovative organizations', where such risk taking can be inbuilt in the ethos and culture of the organization. I am also going to share my thoughts on how India can become a leader in technology, if it learns to take risks.

Let me begin by sharing some of the joy and excitement I have had in my own research career by chasing anomalies, looking for points outside the prediction line, from failed experiments and from lucky accidents.

Velocity independent transport coefficients

I began my career in non-Newtonian fluid mechanics and rheology. Non-Newtonian fluids are complex fluids, such as polymer solutions and melts, suspensions, some biological fluids and so on. They are structured fluids and give rise to several bizarre flow phenomena. I remember standing right here in this Faculty Hall and delivering a lecture on 'Fascination of non-Newtonian fluids' about ten years ago, which has appeared in *Current Science*¹. I am happy to see that the Faculty Hall was as crowded then as it is today. The experiments that I am going to speak about today are simple model experiments, which gave us results, which were totally counter-intuitive.

Let me begin with an anomalous observation that was reported in late sixties but explained by us in late eight-

*Dedicated to Prof. S. Ramaseshan on his 80th birthday.

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ies. Convective heat transfer in rapid external flows has been extensively studied. It is well known that the heat transport coefficient increases with an increase in the velocity. However, in late sixties, it was found that when such heat transfer experiments are conducted in dilute viscoelastic polymer solutions across tiny cylinders, something amazing happens. At a particular critical velocity, the heat transport coefficient becomes independent of the velocity! Rapid external viscoelastic flows was a subject of intensive study in late sixties. Most efforts were focused on using the conventional boundary layer analysis pioneered by Prandtl in the early part of the century. In 1980, we broke new grounds by challenging the conventional wisdom². We argued that at the leading edge of the cylinder, it is the elastic stresses that balance the inertial ones, and not the viscous ones. This led to the formulation of an 'elastic' boundary layer concept, the thickness of such a boundary layer being independent of the free stream velocity.

Size independent particle dissolution

As a chemical engineer, I have an interest in looking at problems of both convective heat and mass transfer. Let me take a mass transfer problem now. A classical problem is the dissolution of a particle in a solvent. If you take a cube of sugar and try to dissolve it in water, you find that the time of dissolution continuously reduces as the size of the cube reduces. This is universally true. But we saw something strange, when we looked at the dissolution of a solid sphere made of a polymer. We measured the time of dissolution as we kept on reducing the size of the polymer particle. We found that the time of dissolution kept on reducing. However, something strange happened. After a particular critical size of the particle was reached, the time of dissolution became constant³. In other words, no matter how small did one make the particle, the time to dissolve it always remained the same (Figure 1 *a*). We saw other anomalies⁴, where an externally small amount of residual solvent had led to an enhancement in dissolution rate by a factor of 100! (Figure 1 *b*). This phenomenon had been a big puzzle of polymer dissolution kinetics for over a decade. The key to the resolution of this anomaly was provided by us through a series of mathematical models⁵⁻⁷ and some probing *in situ* experiments on particle dissolution by using high resolution solid-state NMR^{5,8} (Figure 2 *a*), which gave us an insight into the events at the molecular level. We detected the crucial role of reptation dynamics as well as the dynamics of the disengagement of the dangling chains from the polymer-solvent interface that was responsible for such a behaviour (Figure 1 *c* and 2 *b*). It also gave us a very simple way of measuring the reptation time. What was equally interesting was that we were able to explain some unexplained anomalies in

the adsorption-diffusion problem in polymer solutions too⁹⁻¹¹ (Figure 3). Again, it was an anomalous observation, which gave us new insights in polymer chain dynamics.

Migrating spheres

Let me move from a dissolving solid polymeric particle to a non-dissolving particle, which is moving through a polymer solution. If you take a polymer solution in a long tube with a large diameter and drop a sphere in the centre of the tube, it attains its terminal settling velocity after some time, which remains constant for a given sphere and a solution under ordinary circumstances. We took a polymer solution and dropped a sphere and measured the terminal settling velocity. When we dropped another identical sphere after the first sphere had settled, strangely the terminal velocity was higher. It kept on increasing with each successive drop, until it reached a plateau¹² (Figure 4 *a*). The second observation was even more strange, that was made by Astarita from University of Naples in Italy in the sixties. He dropped a sphere at the centre of the tube. Then he dropped another sphere, not at the centre, but slightly away from the centre, after the first sphere had settled at the bottom. Curiously enough, the second

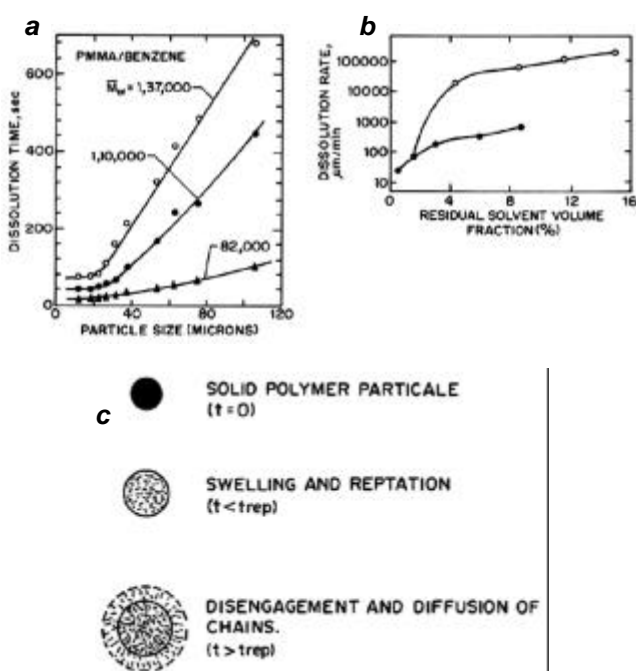


Figure 1. *a*, Experimental data³ on the dissolution time of monodisperse PMMA particles in benzene. The dissolution time asymptotically reaches a constant value below a certain particle size. *b*, Data indicating significant enhancement of dissolution rate due to presence of a residual solvent⁴. *c*, A schematic of the physical processes³ accompanying dissolution of a polymer particle in a solvent. t_{rep} is the reptation time of a polymeric molecule. Reprinted from *Chem. Eng. Sci.*, vol. 49, Devotta, I., *et al.*, The life time of a dissolving polymeric particle, pp. 645-654, © 1994, with permission from Elsevier.

sphere refused to follow the line of drop. It tended to move towards the centre line, a path that the first sphere had taken, and then settled along the centre line. For several decades, these phenomena remained unexplained. It was only in nineties that we found an explanation. The systems, in which these anomalies were observed were solutions of long chain polymers, such as polyacrylamide. We recognized the critical role of energetic interactions in such solutions for the first time. We showed that such interactions lead to the formation of transient networks, which break rather easily, but take a long time to reform (Figure 5). All the previous efforts were based on interpreting these phenomena by using models, which took into account networks formed by physical entanglements alone, namely physical networks. Several anomalies, which were associated with the behaviour of such

solutions were explained by us¹³⁻¹⁵. In fact the strange double overshoot during stress growth experiments by Kulicke and his colleagues¹⁵ had baffled researchers for almost two decades (Figure 6). Again, it was our continuous chase of these anomalies, which led to the development of the Energetically Crosslinked Transient Network (ECTN) model (Figure 4 b and c). Recently, we also provided a proof of the molecular level events that take place in the breakage and reformation of these networks by doing some unique Rheo-NMR experiments¹⁶, which substantiated our intuitive arguments used in the model (Figure 7).

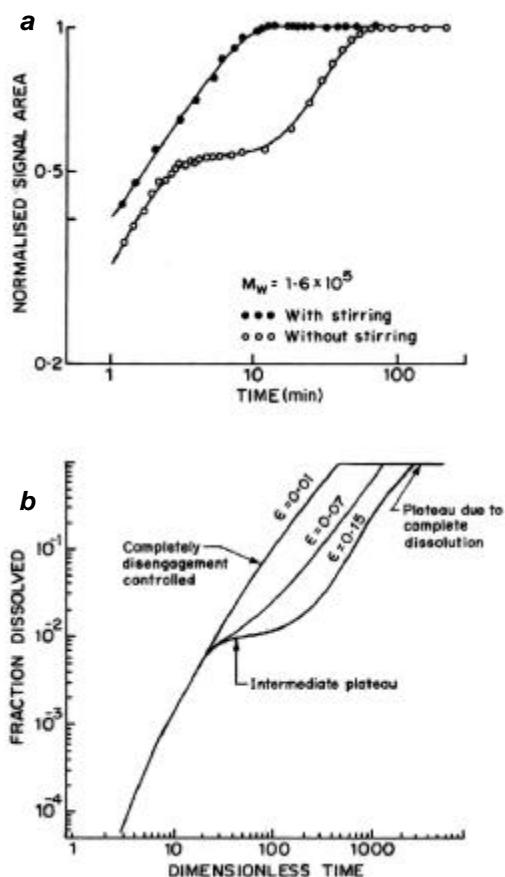


Figure 2. *a*, *In situ* NMR data⁵ on dissolution of polymer in the presence and absence of stirring. In the presence of convection the dissolution rate is governed by the disengagement of polymer chains from the surface of the particles. In the absence of flow the overall rate is controlled by disengagement dynamics at initial times and at longer times the diffusion process becomes rate controlling. The plateau seen in the figure signifies the change in the rate limiting processes. M_w is the weight average molecular weight of the polymer. *b*, Predictions from a mathematical model developed in our work⁵, which captures the physics of diffusion and disengagement control mechanisms. ϵ is the ratio of diffusion length scale to the half-length of the polymer particle. Reprinted from *Chem. Eng. Sci.*, vol. 50, Devotta, I., *et al.*, Unusual retardation and enhancement in polymer dissolution: Role of disengagement dynamics, pp. 2557–2569, © 1995, with permission from Elsevier.

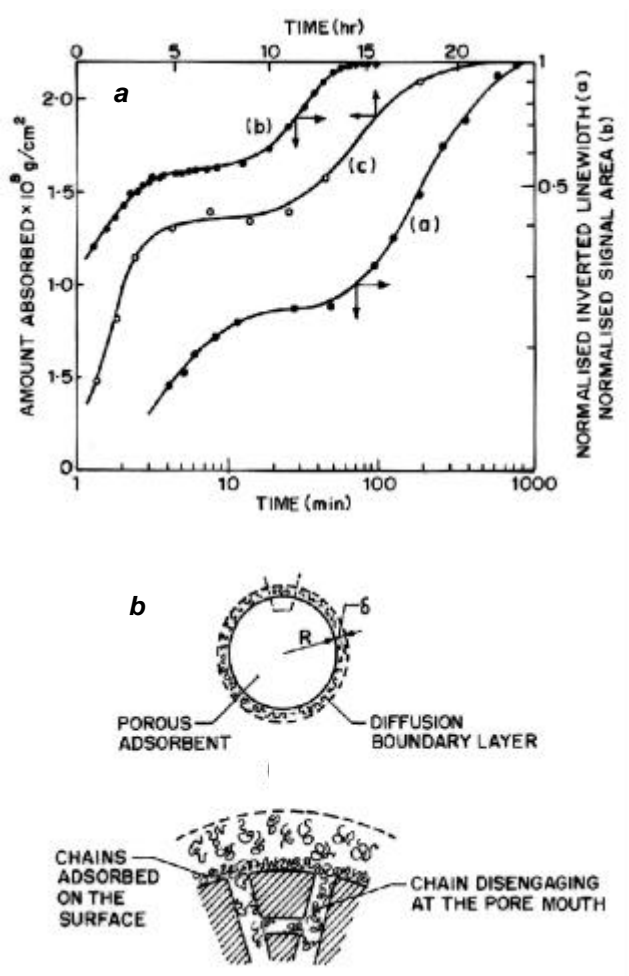


Figure 3. *a*, Similarity between the swelling-dissolution dynamics and the adsorption-diffusion dynamics. Curves (a) and (b) show NMR data of normalized inverted line width of the proton signals from the polymer⁹, which indicate the mobility of the chains. The curves (a) and (b) thus show the presence of a double plateau in the swelling-dissolution kinetics. Curve (c) shows data¹⁰ on adsorption of a polymer as a function of time. These data also show the presence of a double plateau similar to that for the swelling-dissolution kinetics, thus underlining the similarity between these two phenomena. *b*, A schematic of the mechanism of adsorption-diffusion problem. Chains diffuse to the particle surface through a diffusional boundary layer, adsorb on the particle wall to form an entangled swollen gel state and then diffuse into the pores of the particles by disentangling from the adsorbed layer. Reprinted from *Chem. Eng. Sci.*, vol. 50, Devotta, I., *et al.*, A new phenomenological model for adsorption diffusion in polymer solutions: role of disengagement dynamics, pp. 1129–1142, © 1995, with permission from Elsevier.

Non-dissolving fibres from water soluble polymers

Let me stay with this problem of dissolution and motion for a little longer. If you take a polymer solution and cool it, or put it in a non-solvent you find that the polymer precipitates out. You can easily redissolve the precipitated polymer, when you warm it up or put it in a good solvent. But something interesting was found by Metzner and his student Rangel-Nafail from the University of Delaware in USA almost two decades ago¹⁷. When they forced a polymer solution to undergo a shear flow in a couette device, the polymer precipitated out even at room temperature. This was explained by accounting for the

contribution of the free energy of deformation of molecular molecules in altering the phase diagrams¹⁸. What was strange, however, was that the polymers, which were precipitated by such a process, would not redissolve, no matter what you did. When the polymer solution was forced to go through a porous disk, they were subject to strong extensional flow. A fibre was formed. It would not redissolve too. It was almost thirty years later, to be precise in 2001, that we showed the role of deformation-induced hydrophobicity to explain this anomalous phenomenon¹⁹.

We used an aqueous solution of flexible polyacrylamide molecules as a model system. We showed that deformation can induce strong cooperative inter-polymer

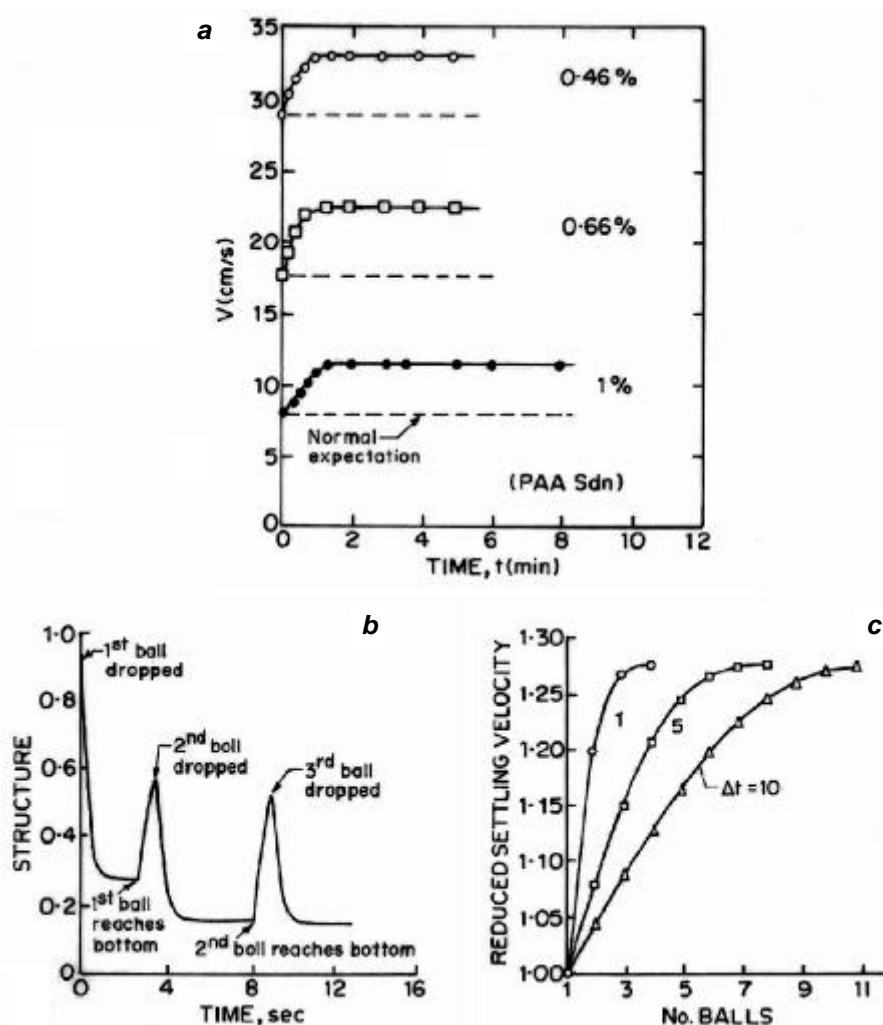


Figure 4. *a*, Experimental data¹² showing that the terminal settling velocity of identical stainless steel balls dropped consecutively one after the other in a polyacrylamide solution increases until a saturation value. *b*, Calculations of the ECTN model^{13,14} which suggests that there exists a 'structure' in the polymer solution formed by temporary energetic crosslinks (such as by hydrogen bonding) that is broken by the shear imposed by the previous ball and which does not recover fully before the second ball is dropped. As a result, the consecutive balls drop through a medium of effectively lower and lower viscosity and therefore have higher terminal velocities. This is shown in *c* by the predictions of the ECTN model^{13,14} for the settling velocities of identical balls that are dropped with time interval of Δt between successive drops. Smaller Δt allows for lesser reformation of the structure and therefore leads to higher terminal velocities.

hydrogen bonds between the stretched polymer chains (Figure 8). Further, the zipping of hydrogen bonds also increased the effective hydrophobicity of the chains and prevented the redissolution of the fibres in water. A clear fall out of the theory was the suggestion that a polymer having a semi-flexible configuration, strong proton donor and acceptor groups and a hydrophobic backbone would, in principle, show a tendency to form strong fibres. The semi-flexibility could be induced physically by either strong shear/elongation flows, or chemically by copolymerizing flexible and rigid comonomers. In principle, such a strategy could be adopted for making silk-like strong fibres by synthetic means at mild conditions.

It is a strange coincidence that we sent our paper for publication in July 2000, where we proposed the possible role of hydrodynamically-induced hydrophobicity in the spinning of spider silk. In 2001, a paper appeared²⁰ in *Nature* on the spinning of spider silk and I quote from it: 'The high stress forces generated during this stage of processing probably bring the dope molecules into alignment and into a more extended conformation, so that they are able to join together with hydrogen conformation of the final thread. As the silk protein molecules aggregate and crystallize, they will become more hydrophobic, which should induce phase separation and hence the loss of water from the surface of the solidifying thread.' We were, of course, delighted, because that was exactly what

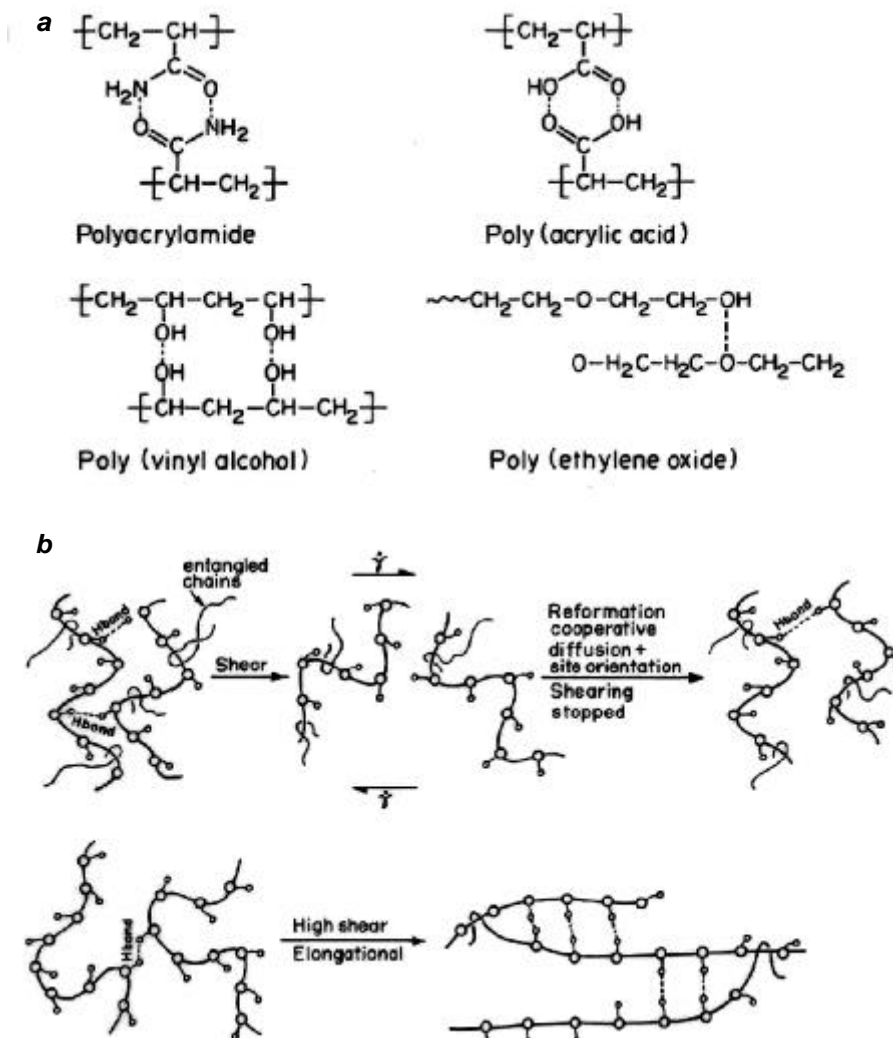


Figure 5. Examples of synthetic polymers showing inter-polymer hydrogen bonding (HB). Such interactions are energetic in nature in contrast to the entropically-driven chain entanglements that are more commonly seen in long chain flexible molecules¹³. HB interactions can be broken by temperature, shear rate, etc. Reformation of HB may indeed be a slow process, since it requires the pairing groups to achieve close proximity and appropriate orientation. However, strong flows can promote cooperative HB by inducing rigidity in the chain.

we had predicted, although through a rather simplistic model.

Serendipity and Indian science

I now come to the issue of serendipity or lucky accidents and Indian science. As we know, sometimes we reach unknown destinations accidentally. This has happened for centuries. In 1786, Luigi Galvani noticed the accidental twitching of a frog's leg and discovered the principle of electric battery. In 1858, William Henry Perkins was trying to synthesize synthetic quinine from coal tar and he came across a coloured liquid, a synthetic dye. This was the beginning of the modern chemical industry. Leo Bakeland was looking for synthetic shellac and he accidentally found Bakelite. That was the beginning of the modern plastics industry. In 1929, a gust of wind blowing over Alexander Fleming's moulds, as we know, created the new antibiotic age. As a proud Indian, it worries me as to why such a wind did not blow over the laboratories

of Indian innovators! Why did we not get one breakthrough, which had the potential to lead India to such a new industry or even an entirely new product through such accidents? Does this mean that those lucky accidents did not at all take place in India? Or if they did take place, were we equipped enough to spot them? What should not be forgotten is that a trained mind is required to spot these accidents. Eyes do not see what the mind does not know. Perhaps there are other reasons. Let me explain this through our own experience.

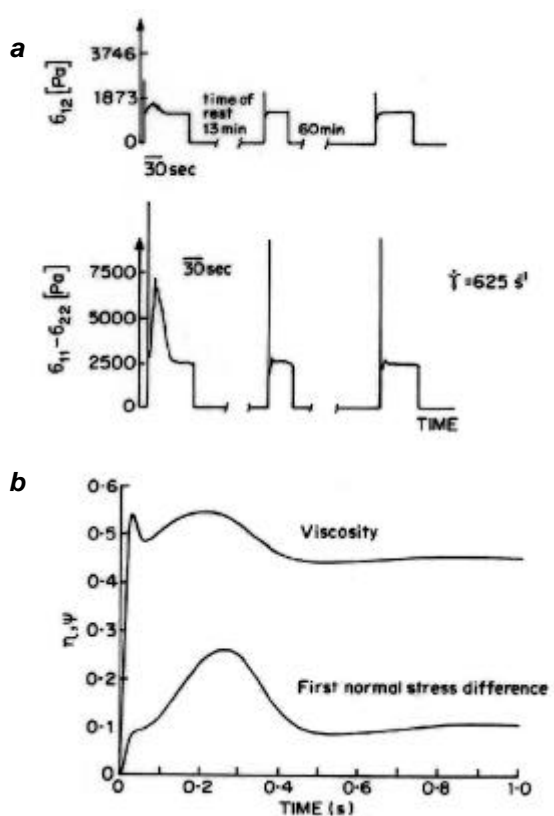
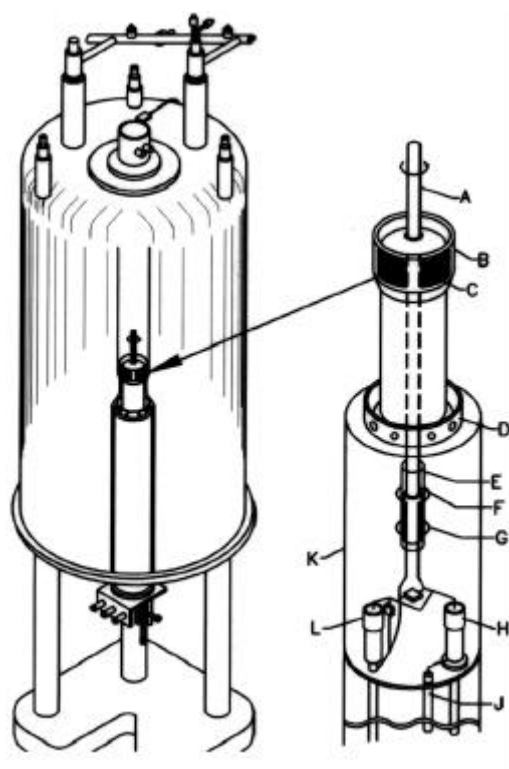


Figure 6. *a*, Experimental measurements on stress growth of viscosity and first normal stress difference for a polyacrylamide solution in formamide¹⁵. The observation of a second prominent overshoot having a much longer relaxation time is clearly seen in the data. *b*, Predictions of the ECTN model¹³ for the stress growth functions of viscosity and first normal stress difference. The first peak is attributed to the rapidly relaxing physical crosslinks such as chain entanglements, while the second peak is attributed to the slower relaxing energetic interactions such as HB. These predictions compare qualitatively with the experimental measurements in *a*.



Conditions	T_1 (ms)		T_2 (ms)	
	CH	CH ₂	CH	CH ₂
Stagnant ($g = 0$)	534	293	50.7	25.6
<i>In situ</i> (shearing at $g = 42 \text{ s}^{-1}$)	458	269	41.2	24.0
<i>In situ</i> (shearing at $g = 85 \text{ s}^{-1}$)	412	263	31.8	21.8
Immediately after stopping shear	473	276	47.3	26.0
14 h after stopping shear	505	277	45.0	24.0
22 h after stopping shear	538	288	37.0	23.0

Figure 7. A rheo-NMR apparatus¹⁶ to measure the relaxation times (*in-situ*) during shear. The table shows the measured relaxation times under stagnant conditions, during shear and on cessation of shear for a polyacrylamide (PAm) solution in water. The decrease in the relaxation times on shear indicates an increase in the relaxation rates. On cessation of shear, the relaxation times recover rapidly but only partially. Full recovery takes an unusually long time. These data provide a molecular level evidence of the presence of a slow recovering network in (PAm) solution. The ECTN model conceptualizes the slow recovery to the slow reformation of energetic crosslinks such as hydrogen bonding, which requires the conditions of proximity and specific orientation of the participating groups to form.

'Missed' gel patterns

We have been working on gels, which are three-dimensional networks. We have been especially interested in gels that imbibe large quantities of solvent, especially water. Our earlier emphasis was on super-absorbing gels, which imbibe 100–500 of water per g of gel. Our idea was not only to synthesize such gels in the laboratory, discover new applications, but also to investigate as to why they work in the way they do. We had a few Ph D students working on these fundamentals.

In mid-eighties, I was in Delhi, when I saw the front cover of an issue of *Nature* carrying this beautiful photograph of spatio-temporal patterns on gels, which were discovered by Tanaka from MIT. I was fascinated, since we had never noticed these patterns. I took a xerox of this cover page, brought it to Pune, and showed it to my Ph D student. I told him, 'Look at what Tanaka has discovered for the first time. Look how he has made it to the cover page of *Nature*. I wish we had discovered these strange patterns, we would have also made it to the cover page of *Nature*.' He looked at me and said, 'but sir, I had observed these same patterns on our gels about two years ago'. I was shocked. I said, 'why did you not tell me about them?' He said, 'Sir, I thought it was not something normal. So I did not tell you.' I trust in his answer and therein lies the malady of Indian science. We are so much in search of the 'normal' that even the seemingly abnormal frightens us. The lucky accident did happen in an Indian laboratory, but the one who saw it was too scared to see the significance of it. Anyway, we got all our students together and told them the importance of such observations. We told them how major breakthroughs have taken place because of people looking for, and some-

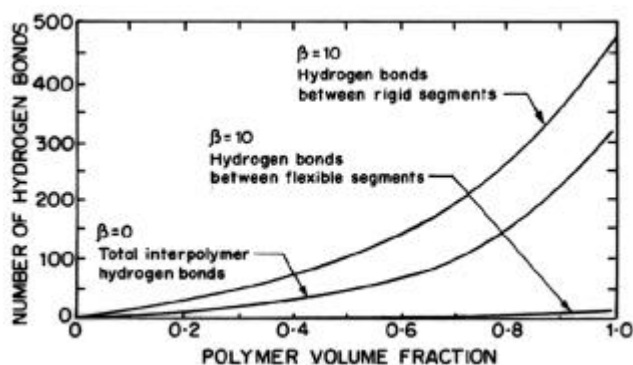


Figure 8. We had developed a model¹⁹ to explain the deformation-induced hydrophobic associations and hydrogen bonding in model associating molecules. The plot shows the increase in the number of inter-polymer hydrogen bonds as a function of polymer volume fraction in the presence and absence of an externally imposed strong deformation rate given by $b = 1g$, where l is a characteristic relaxation time of the polymer. This concept of deformation-induced hydrogen bonding and hydrophobicity has interesting relevance to how spiders spin their webs.

times when they get lucky, actually noticing such accidents. There was a cultural shift and it did pay a rich dividend, but almost ten years later.

Accidental discovery of macroscopic self-organisation in gels

I am located in Delhi now but I am in my laboratory during weekends with my students. Otherwise, I can only keep in touch with them by e-mail or by phone. One night at around 11 pm, I got a call from Shiny Varghese, who was doing her Ph D with me in National Chemical Laboratory in Pune. An excited Shiny told me that she had found something fantastic. Normally, in gels, when volume transitions occur, a gel cylinder becomes a larger cylinder and vice versa. A gel sphere becomes a larger sphere and vice versa. She told me that she had found that a gel cylinder that she was experimenting with spontaneously turned into a hollow sphere with a coconut-like structure (Figure 9). And what is more, she could reverse this process too! We had a breakthrough for the first time ever, since such a magical transition and self-organization at a macroscopic level was never observed before²¹. It was in the seventies that Tanaka's group in MIT had shown how a small gel sphere could undergo a volume transition. This bending had made it possible to make the gels 'mobile'. But the sphere had remained a sphere. It was in the eighties that the Japanese had shown a gel cylinder or a slab could be made to bend by partial contraction of one face. But the cylinder had remained a cylinder. Ours was a clear breakthrough, where a cylinder spontaneously turned to a hollow sphere and that too reversibly! From a scientific view point, our observation was highly significant. Amphiphilic molecules self-assemble into micelles or vesicles. Whereas these measure a few micrometres in dimension, our gels showed self-organisation on macroscopic length scales of the order millimetres! As an aside, I am sure, that if we had not encouraged students to spot such lucky accidents, we would have discovered it on the front page of *Nature* again, after someone from MIT or Cambridge found it!

Sometimes serendipity knocks on your door, but you do not hear it. The discovery of cyanoacrylate adhesives, popularly known as Superglue, is a classical case. Harry Coover of Eastman Chemical Company was assigned the problem of finding an optically clear plastic from which precision gunsights could be cast. He was working with some cyanoacrylate monomers, which showed promise, but he was plagued by a recurring problem: everything these monomers touched stuck to everything else, which he recorded. However, he did not see this as serendipity, just as a severe pain! He was thinking about gunsights only, and nothing but gunsights. The adhesive qualities of these monomers were a serious obstacle in his path. The research was successful, but the end of the war brought

this project to an end. He forgot the stubbornly-sticking cyanoacrylates. Serendipity had knocked, but he did not hear it.

Moving ahead a few years to 1951, there was a need to discover stronger, tougher and more heat-resistant acrylate polymers for jet plane canopies. Coover was now supervising a new crop of eager young chemists who were investigating the properties of the same cyanoacrylate polymers that I had been working with earlier. The

monomers were difficult to make, even more difficult to purify and still more difficult to analyse for purity. Someone in the group prepared what he thought was a pure sample of ethyl cyanoacrylate and decided to measure its refractive index in order to characterize its purity. The measurement was made and recorded. When the scientists attempted to separate the prisms, they could not! They were worried that the refractometer was ruined. Coover, however, suddenly realized that what they had

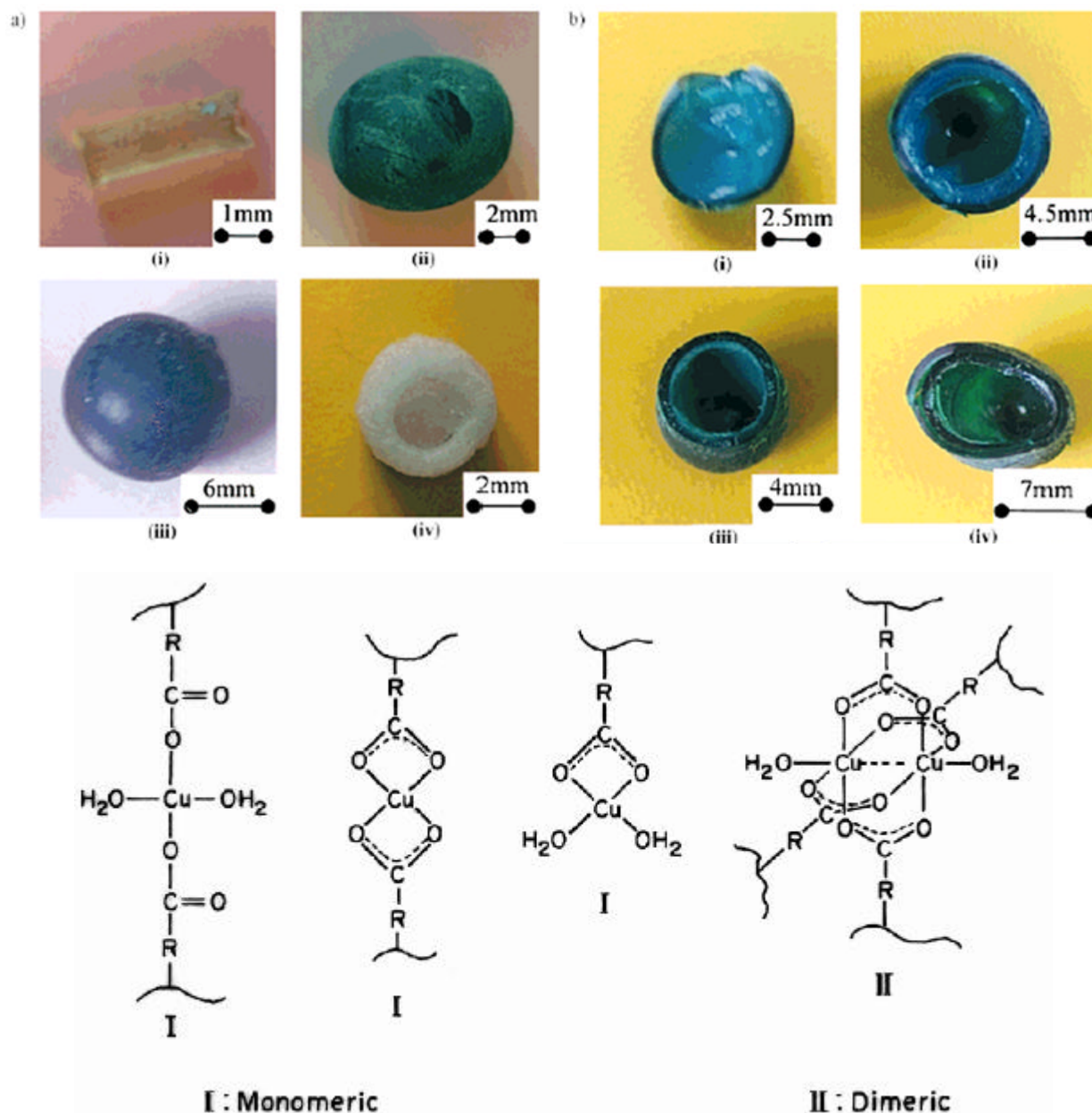


Figure 9. A novel macroscopic self-organization²¹ of a hydrogel when immersed in a CuCl_2 solution. The hydrogel made from acryloyl-6-amino caproic acid has a pendant hydrophobic chain of five methylene units and a terminal carboxyl group. In its ionized state the carboxyl ion coordinates with Cu^{2+} to form a monomeric complex, which converts into a dimeric complex with time. This complexation drives the shape organization from a cylindrical state to an ellipsoidal or a spherical shape depending on the aspect ratio of the initial cylinder. Further, the self-organized gel develops a hollow interior that is driven by rupture of the interior followed by a layer-by-layer deposition of the dimer complex on the outer walls. The phenomenon is completely reversible on removal of the complex.

was not a useless instrument, but a unique adhesive. Serendipity had given him a second chance, but this time his mental processes were fully alert. Immediately, Coover asked the scientists for a sample of his monomer and began gluing everything he could lay his hands on – glass plates, rubber stoppers, metal spatulas, wood, paper, plastic – in all combinations. Everything stuck to everything, almost instantly, and with bonds that could not break apart. In that one afternoon, cyanoacrylate adhesives were conceived, purely as the result of serendipity. These adhesives not only had a significant impact on consumer and industrial applications, but also became a promising answer to a surgeon's dream of a tissue adhesive.

One cannot help wondering as to how many potentially important inventions lie dormant in the recorded observations of scientists, which at that time were judged to be irrelevant to their research objective. This should serve as a reminder to all of us to be open-minded and curious enough to pursue unexplained events and unexpected results that may unlock new secrets and lead to new and exciting discoveries in the future.

Self-healing gels discovered through failed experiments

We have ourselves gone through such a 'sticky' experience. The same gels, which showed those magic attributes of self-organisation that I referred to earlier, were being studied by us using scanning electron microscopy. We just could not manage to get the picture of a single gel bead. They were always sticking together. We were totally frustrated. And then it suddenly dawned on us that these 'failed experiments' were 'successful experiments' since, for the first time, we were witnessing the phenomenon of 'self-healing' in gels. Such a phenomenon of self-healing has been demonstrated by scientists in other materials. Self-healing is common in biological systems. Here healing occurs by the process of cell multiplication and tissue growth. A cut or a wound heals with time leaving behind only a scar or the 'weld line'. Self-healing is also seen in other materials such as ice and polymers. When two ice-cubes are pressed together, healing is achieved by formation of multitude of hydrogen bonds across the interface. In the case of linear polymers, self-healing is achieved by reptation of chains. Unlike linear polymers, crosslinked polymeric networks cannot heal spontaneously owing to the lack of reptation ability of the network chains across an interface. Therefore, what we had demonstrated was unique.

Further, the discovery of this phenomenon is fundamentally important, since gels are being looked at as potential biomimicking materials. Sensitivity, selectivity, mobility, memory, self-organisation, self-healing and enzyme-like activity are some of the attributes of any potential candidates for mimicking life. Out of these, it

was our research group in National Chemical Laboratory that demonstrated, self-organisation²¹, self-healing²², and for the first time, enzyme-like activity^{23,24}. Interestingly, the enzyme-like activity was demonstrated by us through meticulously planned experiments using several components of known knowledge ranging from molecular imprinting to volume phase transitions in gels. However, self-organisation was demonstrated by us due to an accidental observation (with an alert student watching it) and self-healing was demonstrated by us due to a failed experiment!

On hard problems and on working hard at them

If you analyse the winners in science, often times you find that they are ones, who chose interesting problems. A key is in the ability to pose, rather than merely solve, high-level problems. Solving an easy problem has a low payoff, because it was well within reach and does not represent a real advance. Solving a very difficult problem has a high payoff, but frequently it may not pay at all. Many problems are difficult because the associated tools and technology are not advanced enough. For example, one may do a brilliant experiment but current theory may not be able to explain it. Or, conversely, a theory may remain untestable for many years. Thus, the region of optimal benefit lies at an intermediate level of complexity. These intermediate problems have the highest benefit per unit of effort because they are neither too simple to be useful nor too difficult to be solvable. Today's competitive science is based on exploration in this domain. But there is no substitute to focusing energy on these difficult problems, which have a handsome pay off in the long run. Difficult problems require confidence, patience and years of hard work too.

Funding risky research at NCL

Can we fund risky research, kite flying or crazy ideas or out-of-the-box thinking? I think we can and we should. Let me share our experience of doing this at the laboratory level, at the CSIR level, and now even at the national level.

When I was the Director of National Chemical Laboratory in early nineties, we set up a 'Kite Flying Fund'. What was the philosophy behind this fund? In science, only those are remembered, who say either the first word in science or the last word in science? India has not done it often enough. Why? Because, among other things, we have not dared, risked, gambled or deliberately funded risky research. We said we will support ideas, which aim to attain some unattainable goals, meet some stretched targets, or follow novel strategies in problem solving, that have never been used before. Here the chance of success may be one in one thousand. This fund generated

a lot of excitement. I remember a fierce competition among scientists, where many innovative ideas sprang up – some of them even leading to a paper or two in *Nature* and *Science*!

Funding risky research at CSIR

When I moved to CSIR, we used the ‘Kite Flying Fund’ concept at NCL to create a ‘New Idea Fund’. We invited the entire chain of laboratories to submit ideas, which had explosive creativity, and where the chance of success may again be even one in thousand. During the last 5 years we have received over 350 new ideas but we have funded only 15 of them; we are so tough on our criteria on what constitutes explosive creativity. This initiative has spurred our scientists to aim for increasingly higher levels of innovation in CSIR and even individual laboratories are setting up such funds now. However, when we first introduced this fund, I remember a well-meaning friend alerting to me that this is going to be an excellent fodder for audit, because by definition, we were supporting failure rather than success.

Funding risky research at a national level

At a national level, we have launched a New Millennium Indian Technology Leadership Initiative (NMITLI). The words ‘technology leadership’ are deliberate. They will continually remind us that we want to create an India, that will ‘lead and not follow’. NMITLI is a vehicle, therefore for India to attain a global leadership position, in niche areas, based on technology advantage by forging true ‘Team India’ partnership with publicly funded institutions and academia. NMITLI looks beyond today’s technology and seeks to build, capture and retain for India a leadership position in the global arena based on technology by synergizing the best competencies of publicly funded R&D institutions, academia and private industry. It is based on the premise of consciously and deliberately identifying, selecting and supporting risky ideas, concepts, technologies, etc. which could be potential winners.

In the short period of two years since its launch, several massively networked projects involving over 150 R&D institutions/academia and around 50 industry partners have been catalysed. This is the biggest Indian knowledge network so far, where the private sector has participated in such numbers and with such enthusiasm. The Government has invested around 100 crores in NMITLI, that is coordinated by CSIR. The projects evolved cover a wide spectrum of technologies ranging from defunctionalization of carbohydrates as building blocks for chemical industry of the future for replacing petroleum-based hydrocarbons; to stimuli sensitive nanoparticle-based drug delivery systems for specific thera-

peutics, to flat panel liquid crystal display systems, with switching speeds that are hundred times faster than the state-of-the art systems! Most of these projects seek to usher in a complete new paradigm in technology perspective with support for risky ideas, daring and creativity.

On risk taking in science

Let me emphasize that risk taking is the key and therefore, in scientific research, there should be no place for those who preserve the systems in a pre-fabricated and unaltered way. A friend of mine, who is a CEO of a company from abroad, once said ‘we do not shoot people, who make mistakes. We shoot people who do not take risks. What do you do?’ I said, ‘In India, we shoot people, who take risks!’ I believe this is true. The most risk averse are government laboratories. In fact, it is more often than not that such institutions are run by rules and regulations than by objectives. The system of S&T audit in our laboratories needs an urgent re-look.

One must understand that manufacturing and S&T are two different endeavours, culturally and operationally. In manufacturing, we look for zero defects and no failures, whereas in science, there is a fundamental right to fail. An interesting analysis has been done by Stephen and Burley in 1997 for Industrial Research Institute, which lists out the significant odds facing would be innovators by analysing consistent data from new product development, potential activity and venture capital experience. It has been shown that there is a universal curve, which illustrates the number of substantial new product ideas surviving between each stage of the new product development process. Indeed, out of 3000 raw ideas (hand written), 300 are submitted, which lead to around 125 small projects, further leading to nine significant developments, four major developments, 1.7 launches and one success. In India, it is the other way around, since if they are abandoned at an intermediate stage, there is a risk of audit objections. When we fund ‘futuristic research’, we are funding risks too. But many times, the view of the future is taken by extrapolating the present. This does not always work out. Indeed the ability to speculate on the future is more difficult now than ever before.

On the issue of funding risky research in industry, my favourite is the company 3M. It has become a leading innovator of products, ranging from the mundane to the breathtakingly complex. This is because the company encourages risk. Take the example of the simple ‘Post-it’ notepad that is so ubiquitous nowadays. It started off as a failed experiment at making a better adhesive. If you are a company in the business of making adhesives then when you are faced with an adhesive that does not bond very well, the immediate instinct would be to shelve the product as a bad ‘invention’. But not in 3M. A creative

employee thought of a brilliant idea of using the poor adhesive to make easily removable note pads – the ‘Post-it’ notepad. Today the ‘Post-it’ notepad is such a wildly successful product. The CEO of 3M, William McKnight, built a company where tinkering by employees is encouraged and an environment is created in which accidents happen. What is more important is that the ideas generated by this tinkering are championed by the management into products that meet real human needs.

In search of ‘irreverence’ in Indian science

Science is an exploration of the nature of reality, both inside and outside us. The emphasis here is on things, which are quantifiable and measurable and on theories, which can be tested and demonstrated; and facts, which can be observed and verified by others. Imagination plays a vital part in both science and art, but in science it has certain constraints. As Feynman has said: ‘Whatever we are allowed to imagine in science has to be consistent with everything else that we know. The problem of creating something which is new, but which is consistent with everything which has been seen before, is one of extreme difficulty.’ At the same time, the difficulty with science is often not with the new ideas, but in **escaping the old ones**. A certain amount of **irreverence** is essential for creative pursuit in science. I believe that if we promote that irreverence in Indian science, by change of personal attitudes, change of funding patterns, creating new organizational values, creating that extra space for risk-taking, respecting the occasional mavericks and rewarding the risk takers, then not only will the fun and joy of doing science increase, but also Indian science will make that difference, that ‘much awaited’ difference.

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