What will it take for Indian science, technology and innovation to make global impact?

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Top ten in the 20th Century

When the Indian National Science Academy (INSA) celebrated its platinum jubilee, I had proposed[1] a five-point agenda for raising the bar on making Indian science, technology and innovation (STI) original, innovative and creative. One of the challenges that I referred to was: '…It is time now that Indian science begins to make a "big difference" to the world of science. They say only two people are remembered in science, those who say the first word and those who say the last word. How many times have we said the first or the last word? We have invariably looked through windows that others have opened up. When are we going to open up new windows ourselves through which others will start looking?'

Indian scientists did open 'new windows' in the past. Jayant Narlikar listed[2] what (of course, in *his* opinion), were the top 10 achievements of Indian STI in the 20th century.

In the pre-1950 era, the first on his list was Srinivasa Ramanujam, who opened so many new doors, some even well after his untimely death in 1920. The second was Meghnad Saha's ionization equation (c. 1920), which opened the door to stellar astrophysics. The third was S. N. Bose's work on particle statistics (c. 1922), which clarified the behaviour of photons and opened the door to new ideas on statistics of microsystems that obey the rules of quantum theory. The fourth was C. V. Raman's discovery that molecules scatter light (c. 1928), the Raman Effect, which opened the doors for a new way to study the internal structure of molecules. The fifth was G. N. Ramachandran's pioneering work in structural molecular biology (c. mid-1960s), which created the Ramachandran Map, which, even today, is at the very heart of elucidation of all protein structures; leave alone his breakthrough on collagen triple helix.

Post-1950, Narlikar listed another five. The first was the development of nuclear power and capability (founded in 1950s). The second was the Green Revolution in agriculture (the 1960s and 1970s). The third was the Indian space programme and satellite fabrication with satellite vehicle launching capability (from late 1970s). The fourth was the work in high temperature superconductivity (since the late 1980s). The fifth was the transformation of the chain of 40 laboratories of CSIR[3] towards an industry-oriented, performance-driven and accountable organization (in late 1990s).

Mental and physical hurdles in Indian STI

Narlikar noted the shift from 'individual scientist in the pre-1950 era' to 'organized science in the post-1950 era'. Further, he made a point that the scientists identified by him in the pre-1950 era were 'Nobel Prize class'. Interestingly, each one of them had 'opened new doors' with entirely 'first to the world' ideas. About generating new ideas, Richard Feynman had famously said, 'The challenge is not to create new ideas, the challenge is to escape the old ideas. To escape the old ideas, we need irreverence.' Therefore, at INSA's platinum jubilee, I had also raised[1] this issue – 'How do we create this culture of irreverence, where our young students will begin to challenge the established? A culture where irreverence will be tolerated and not demolished? Where there will be a tolerance for risk-taking and failure?'

In fact I pursued the issue of irreverence in a guest editorial in *Science*[4], titled 'Irreverence and Indian Science'. An erudite editorial[4] on this guest editorial was written by Balaram, which appeared in *Current Science* within a record time of 10 days!

To my mind, here are some obvious fundamentals that have to change for making Indian science and technology more original and innovative[4–8].

The first is the issue of our cultural inheritance that inhibits questioning. India has the dream of becoming a 'start-up' nation. Israel is dubbed as a 'start-up' nation in terms of the highest number of new technology start-up companies. But it is so because young Israelis always challenge and question and are highly entrepreneurial. Both these attributes need to be significantly improved in India.

Second, our education system suffocates originality. There is a need for innovation in our education systems – getting rid of the rigid unimaginative curricula, replacing 'learning by rote' by 'learning by doing', and phasing out examination systems based on single correct answers.

The third is bureaucracy, where paper becomes more important than people, where 'appearing to be right' takes a precedence over 'being right', where rule book dominates over the objectives and where decision-making time cycles are larger than product life cycles.

But then there is a fourth fundamental of subcritical Indian R&D funding.

At the time of celebration of India's 60 years of independence, the magazine *Business Today* published a special issue on '25 challenges for India'. A controversy had erupted at that time about the 2005 Nobel Prize in Physics having excluded E. C. G. Sudarshan, a scientist of Indian origin. Against that background in 2006, I was invited to write[9] an article 'What will it take for a resident Indian to win a Nobel Prize?'.

Among other things, I had said; 'Indians can always argue that we do not win Nobel prizes because our investment levels are low. The US spends $ 2.50 billion (Rs 1,125,000 crore) on R&D as against India's $ 0.5 billion (Rs 22,500 crore). Size of the funding is, of course, important. You build large critical mass in a given field, setting up a competition. You empower the scientists hugely with modern tools so that they can run faster and arrive at the results first.'

Can't have first word in science with subcritical infrastructure

Take, for example, the recent excitement[10] on hydrogen sulfide (H_2S) smashing the previous superconductor temperature record of –110°C by demonstrating superconductivity at –70°C. This feat was achieved by experimenting at an extreme pressure of 150 gigapascals. Why is it that we in India were not the first to achieve this feat? Ajay Sood at IISc told me that they do not have a facility to go beyond 40 gigapascals!

Narlikar in his list of top 10 achievements in the post-1950 era includes the work on high temperature superconductors in late eighties, led by pioneers like C. N. R. Rao. Rao recalls[11] his first paper on La_2CuO_4 like compounds with late Ganguly was published as early as 1971. And it was precisely such series of compounds that won the Nobel Prize for Bednorz and Muller in 1986. Ganguly was my colleague in National Chemical Laboratory and he used to tell me how he wished they had the liquid helium facility to test such compounds for high temperature superconductivity at IIT (Kanpur) a decade earlier! Yes, it is a 'what if' argument. But who knows!

Most of the global efforts using X-rays are now based on synchrotron radiation. There are 50 synchrotron facilities operational in countries like China, Brazil, Korea, even in Thailand. But India does not have a state-of-the-art synchrotron facility. Indus-2, which became functional only recently, is a good technology demonstrator but a second-generation one. Many researchers tell me that for analysis requiring synchrotron radiation, they have to depend on foreign sources like Elettra (Italy). It is obvious that to be able to say the first word in science, we must give Indian scientists a level playing field.

One must hasten to add here, however, that it is the power of the 'idea', not the power of the 'budget' that counts in the final run. While addressing young Indian science students, I always tell them that resource constraints should not deter them from creating great ideas. And then I give the example of the simple inexpensive scotch tape experiment by Andre Geim and Konstantin Novoselov that created graphene, a Nobel Prize winning discovery![12]

Murthy challenge for Indian STI

There has been much debate around a convocation lecture delivered by N. R. Narayana Murthy at IISc earlier this year. He had raised two questions in his convocation address[13]. Let us separate them. The first was 'what the contributions of Indian institutions of higher learning … have been over the last sixty plus years to make our society and the world a better place?'. There is no question that contributions of Indian scientists to Indian society (with national S&T budgets less than that of R&D budgets of a single American company) have been extraordinary[14–18]. Rao's response[19], the first in the *Current Science* series, has just appeared, which passionately highlights this.

The second question of Murthy is a more difficult one. 'Is there one invention from India that has become a household name in the globe? Is there one technology that has transformed the production of global corporations? Is there one idea that has led to earth-shaking invention to delight global citizens?'

The report by Science Advisory Council to the Prime Minister (SAC-PM) cites an example of an Indian invention[20], which made a 'global impact' at the level that Murthy is talking about – not in the past sixty years though!

In 1895, J. C. Bose demonstrated for the first time in the world that communication signals could be sent through electronic waves (over a distance of up to a mile at the time) without the use of wires. He was the first in the world to use a semiconductor crystal (galena) as a detector of radio waves. It is the sort of microwave radiation that Bose demonstrated in Kolkata that drives the ubiquitous mobile phone today. Other striking applications of millimetre waves are satellite communication, remote sensing, etc. So here is an example of ideas being born in India, but applications getting developed abroad.

In my book '*Reinventing India*', I have given a lot of examples of the pleasure and pain of Indian innovation[21]. Pleasure, because Raman Effect was discovered in India. Pain, because Raman scanner was developed in the West. Pleasure, because wealth has been created out of new Indian ideas. Pain, because that wealth has been created abroad, not in India!

Indian science led Indian innovation: The big challenge

The painful fact is that it is not an original 'invention' but a successful 'innovation' that puts that invention into practice on a global scale that makes an impact.

I wrote on the Indian challenge of fostering such 'science led innovation' in the SAC-PM Report[17]. The very first point on the agenda was about building a powerful national innovation ecosystem[22]. The essential elements of a powerful national ecosystem comprise physical, intellectual and cultural constructs. It includes idea incubators, technology parks, a conducive intellectual property rights (IPR) regime, smart and fast IPR capture systems, balanced regulatory systems, strategically designed standards, proactive government support systems (including aggressive public procurement policies for indigenous innovations), industry leaders, who believe in innovation led growth and invest heavily in R&D, scientists with an aspiration to become technopreneurs, potent inventor–investor engagement, 'adventure' capital and passionate innovation leaders.

I have elaborated[17] on how the past deficiencies in *each* of these twelve key elements have hurt India's ability to move from invention to innovation. The worrisome point is that India's innovation ranking in the Global Innovation Index[23] has slipped from 62 (2011) to 64 (2012) to 66 (2013) to 76 (2014). So we need to change – and in a hurry!

Adventuring in Indian STI: view from a personal lens

Murthy had listed at least ten major inventions that MIT in USA had created in the last fifty years, from GPS to e-mail, microchip to fax machine and so on. He had then rightly said 'These inventions happened because students and faculty at MIT walked the untrodden path, asked the unasked questions, used their intellectual prowess to take huge leaps, and demonstrated unusual courage to achieve the plausibly-impossible'.

Can we trigger such daring spirit in Indian science by some bold and innovative funding? For whatever it is worth, I will share my own efforts to achieve this, first at a laboratory level, then at CSIR level, and then at a national level.

While I was the Director of National Chemical Laboratory (1989–95), we created a 'Kite Flying Fund'. A small budget was reserved for funding proof of concept studies on some truly out-of the-box ideas. The chance of success could be even one in hundred. Suddenly, there was an excitement in the air, since failure did not scare the scientists. Some top class research publications (e.g. in

Science) emerged – but no great breakthroughs.

When I was the DG of CSIR (1995–2006), we created a similar 'New Idea Fund'. Again a small budget to support out-of-the-box ideas. Chandrakumar's early US patents on spin computing[24,25] were a good example of what could be done. But, in general, it turned out that the problem was not the lack of funding, it was the lack of breakthrough ideas!

Indian STI as a leader and not a follower

At a national level, in 2000, we conceived and operationalized the New Millennium Indian Technology Leadership Initiative (NMITLI), the key word being 'leadership'. It was a bold public–private partnership, where grand challenges were taken up by the best brains in India in a 'Team India' fashion. For example, a globally competitive, affordable, portable and versatile bioinformatics software package 'Biosuite' was created by Tata Consultancy Services with as many as 19 institutional NMITLI partners in a record time of 18 months!

One NMITLI grand challenge was to create 'two orders of magnitude faster liquid crystal display (LCD) device'. With NMITLI support, the Centre for Liquid Crystal Research did create new LCD materials which had two orders of magnitude faster response time. The invention was patented[26] but it did not lead to innovation, as India did not have the innovation ecosystem to capitalize on this breakthrough.

NMITLI posed a grand challenge on creating a new molecule that will clear tuberculosis (TB) in 2 months, rather than the conventional 6–8 months. Lupin and its NMITLI partners created an entirely new molecule having superior antimycobacterial activity for treatment of latent TB and treatment of multidrug-resistant TB[27], while also achieving the 2-month target. It went successfully until phase II and then some issues have arisen that need to be addressed. But the point is that Indian scientists did rise to the challenge and did discover a new TB molecule after Rifampicin, which was discovered 40 years earlier!

NMITLI posed the challenge of creating a breakthrough leather processing technology that was biological (clean) rather than the currently practised chemical (polluting). The challenge was met. A novel enzyme-based leather technology has been demonstrated that can give India global leadership in cleantech leather processing.

NMITLI posed the challenge of creating a novel indigeneous fuel cell technology. The challenge was met. It is presently undergoing testing with an industrial partner, who is also a potential user at a truly massive scale across the nation. The key here is that the entire manufacturing ecosystem has been developed with supply of all the components, catalysts, accessories, etc. from within India so that a true 'make in India' dream can be realised. Order-of-magnitude cost reductions have been achieved in some critical components. Novel next generation fuel cell component have been invented and globally patented. Although it is early days, India has the potential to lead in this critical fuel cell technology.

NMITLI raised the bar on creating products that are globally protected by patents. Bigtec Labs, Bengaluru with NMITLI support, developed unique a microPCR device – Truelab Uno™ for real-time PCR based nucleic acid detection of pathogens. Patents were filed in around 130 countries, and have been already granted in over 70 countries!

Was everything in NMITLI successful? No. There were failures too. But that is what happens when you wish to lead and not follow! NMITLI is not just a programme, it is a new spirit, it is a bold message that Indian science will dare to try, unafraid of failure!

Indian STI now raring to go

Despite the fall in India's global innovation rankings[23], Indian science is moving upward. India ranked sixth in the number of total annual research papers published in 2013; an improvement from the 12th rank in 2005. But India was number one in two things. First, its compounded annual growth rate was the highest at 13.4%. Second, in terms of research papers per GDP per capita, India was number one.

Indian innovation is changing the very dictionary of innovation. New terms like frugal innovation, inclusive innovation, reverse innovation, nanovation, more from less for more (MLM) have been inspired entirely by India's unique strength[28,29] in delivering 'affordable excellence'. India became the first country to succeed in its maiden mission to Mars – at an astonishingly low cost! Mars Orbiter Mission was a shining case of India demonstrating global leadership in 'affordable excellence'.

Indian industry is raising the bar in research and innovation. Tata group of companies have instituted[30] an annual award called 'daring to try', for the boldest idea that failed. Mahindra has posed[31] India's biggest innovation challenge with the US$ 1 million Rise Prize for spurring breakthrough disruptive innovation.

But what about young start-ups? India has the fastest growing start up ecosystem in the world today[32]. Currently it has 12,340 start-ups. Ten-year projections are pegged at 100,000 start-ups with a $500 billion combined market value. Look at the great valuations of current Indian technology start-ups: Flipkart ($ 11 billion), Snapdeal ($ 5 billion) and Ola ($ 3 billion), who are riding on the wave of digital technology. But these are based on the clones of ideas born in the USA. Our dream should be to create these Indian start-ups cutting edge science & technology based ideas that are born in India and fostered in an Indian innovation ecosystem. We can proudly look at Kiran Mazumdar's Biocon, starting in a garage with a seed capital of Rs 10,000, Biocon has grown into Rs 29.3 billion annual turnover (2014) enterprise! We need more of Kirans and Biocons.

Someone has said that India is a number one exporter of talent in the world. How true. Satya Nadella is the CEO of Microsoft. Sundar Pichai is the CEO of Google. It is time that we raise our ambition to not just leading the Googles and Microsofts of the world, but creating them in our own Indian innovation ecosystem. This can be achieved if only we base this ecosystem on the strong foundation of 'Talent, Technology and Trust' as I espoused recently in my convocation address at IIT Indore[33]. And the 'trust' part of it is all about trusting our young, when they take the untrodden paths, ask the unasked questions and aim to achieve the plausibly impossible, just as Murthy alludes. When we do this, India will no longer remain exporter of great talent but that of great technology, with many global firsts, some of which, hopefully, will be game changing globally.

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The science of inequality and the inequality of science

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Rising inequality at a global scale has been a matter of concern for quite some time. In an article published in *Science* more than a decade ago, the then UN Secretary General had said, 'A generation ago, people in the top 20% were 30 times as rich, yet will not give 0.3% of their income for the poorer 80% of the humanity'[1]. Estimates reported[2] last year showed that less than 1% of the global population owned more than 44% of the total global wealth, while 90% owned less than 15%. Two scathing reports by Oxfam, one of which also talked about inequality in India, recently made it to the front pages of many Indian newspapers[3].

As both inequality and growth are well-trodden areas of economics, should a physicist or a chemist dare to venture into an unfamiliar territory? The answer is a hesitant 'yes' for two reasons. First, history shows that extreme and persistent inequality is often a prelude to war between nations, violent social unrest and large-scale destruction of national wealth. India, with a large number of poor people, about 40% or more in 2010 both using US$ 1.25 a day and multidimensional poverty index measures, must be especially alert to such unpredictable events[4]. Second, economics unlike physical sciences has very little predictive ability as has been proved time and again in history. Furthermore contrary to the claim of many of its practitioners, it is not a value-free subject. Policy prescriptions and numbers that are supposed to deliver and indicate rapid growth must be subjected to special scrutiny because they often hide other crucial numbers.

Two centuries of data on the wealth of the rich nations, the historical distribution of such wealth, and a narrative largely free of technical jargon has been recently published[5]. It has attracted considerable attention and the overall validity of the data is well accepted. The most important finding is the following inequality illustrated as

$$r > g. \qquad (1)$$

It is found that from about the time of the Industrial Revolution, the average rate of return on capital (r) has always been greater than the rate of growth (g) of the economy. The overriding importance of eq. (1) therefore lies in the fact that it is based on hard, first of its kind, empirical data not reported till recently for economic theorizing.

A chemist may be forgiven if eq. (1) reminds him of a universal natural law that has been known for almost 200 years. The earliest analytical formulation of this law, namely the second law of thermodynamics (SLT), was published by Sadi Carnot who wondered about the maximum possible efficiency of an ideal steam engine and the source of its