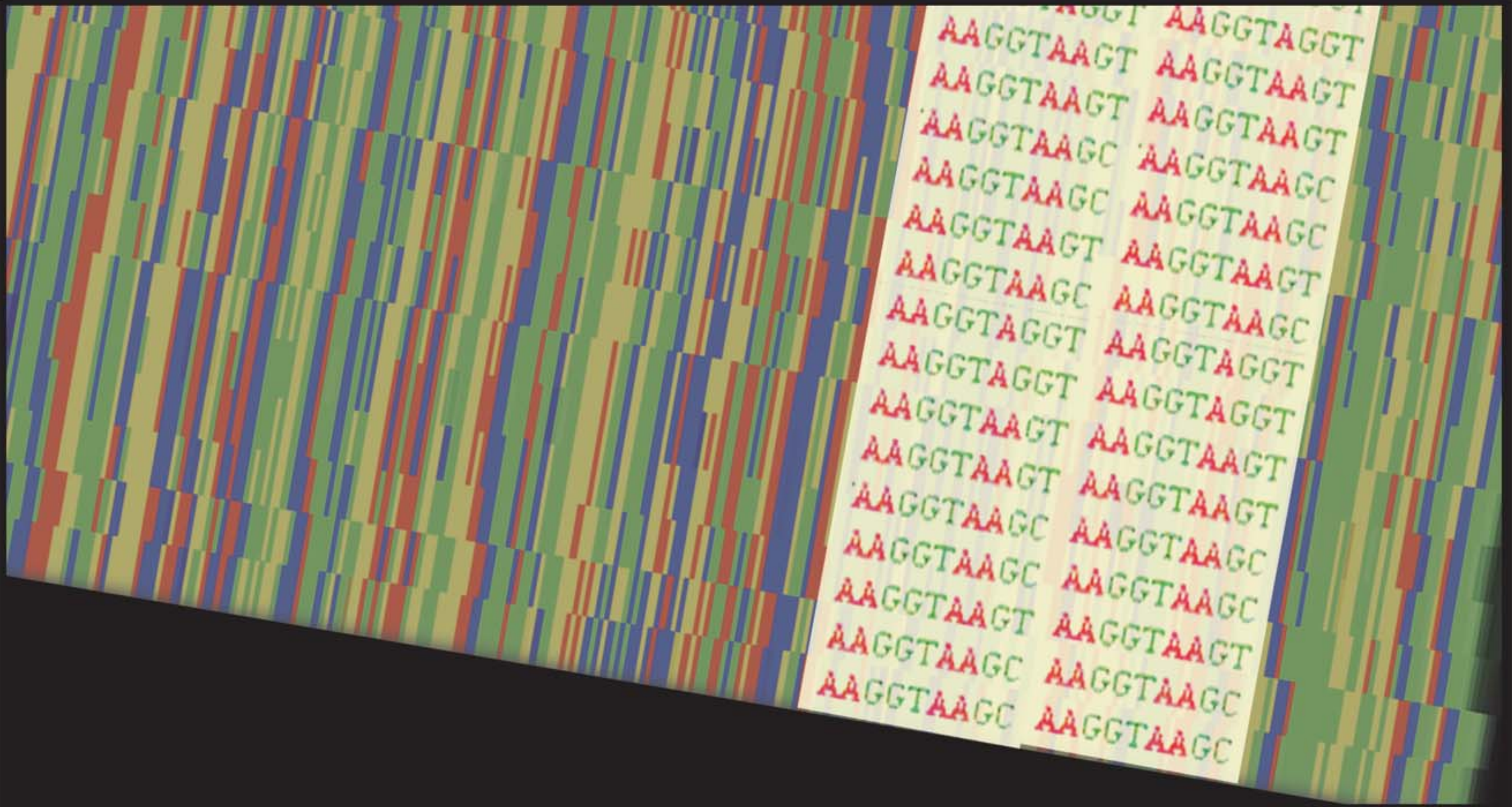

INDIA AS A GLOBAL LEADER IN SCIENCE

2010

SCIENCE ADVISORY COUNCIL TO THE PRIME MINISTER


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SCIENCE ADVISORY COUNCIL TO THE PRIME MINISTER

Department of Science & Technology,
New Mehrauli Road, New Delhi - 110016.

A VISION FOR INDIA

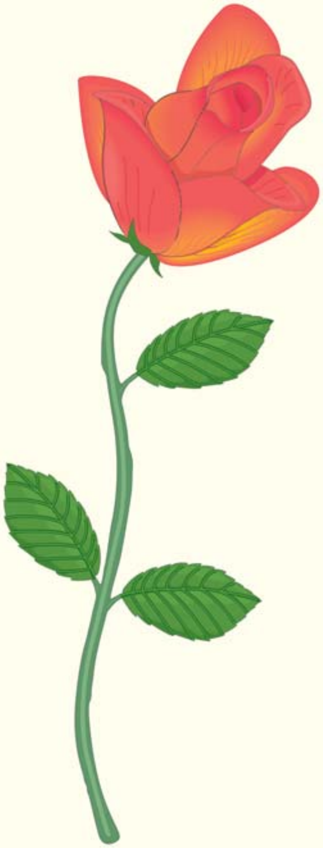
In the next two decades, India is likely to become an economically prosperous nation and move significantly towards being a far more inclusive society, with the bulk of its population gaining access to facilities for education and health care and living a life with hope and security. To realize such a vision, it is essential that science is at the heart of the strategy that the next stage of national development demands. In what follows, we present a vision for the growth of Indian science that can help the strategy succeed, and a road map for India to emerge simultaneously as a global leader in science.

सत्यमेव जयते

प्रधान मंत्री

Prime Minister

FOREWORD



I am delighted that the Science Advisory Council to Prime Minister under the chairmanship of Prof. C.N.R. Rao has prepared this valuable document, "India as a Global Leader in Science" which makes a realistic assessment of the opportunities that lie ahead and the challenges that we face in developing strong capabilities and acquiring global leadership in the area of science.

The document brings out clearly that for India to become a knowledge-based society and to be a world leader in science, we would need to re-double our national efforts to promote scientific temper, strengthen S & T infrastructure, expand our educational base, establish centers of excellence, foster a culture of innovation and channelize greater investments in research and development. We need to create a robust enabling environment for harnessing the creative energies of our youth, which can make a visible impact in improving the quality of life of our people.

I do hope that the ideas contained in this vision document will inspire our scientific community , entrepreneurs, administrators, policy makers and civil society to search for solutions that would help build an inclusive, economically and socially vibrant, creative and an enterprising India, and to pursue excellence in science and technology for global good.

New Delhi

26 August, 2010

(Manmohan Singh)

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INDIA'S PLACE IN THE WORLD OF SCIENCE TODAY

As we near the end of the first decade of this new century, there is a growing perception around the world about the emergence of India as one of the potential global leaders in Science. (In this report, the word science is used as a generic term that includes mathematics, engineering, technology, medicine, agriculture and other related subjects.) The US National Academy of Sciences (NAS) published an influential report in 2005 titled ***Rising above the gathering storm***. The storm referred to in this report is concerned with the emergence of other global leaders such as China and India in science, and the challenges that such a development would pose to the position of the US in the world of science (Box 1). Interestingly, the US President has spoken about young people in China and India working round the clock hungry for knowledge, and how jobs in Buffalo may be lost to Bangalore and Beijing.

We should resist the temptation to get carried away by the NAS report, since India is yet to become a major force in global science. The creation of new scientific and technological knowledge is largely concentrated in three areas of the world: the US, Western Europe and the North-east Asian hub (Japan, South Korea, China and Taiwan), with a few peaks in Russia and Australia (Graphic 1). India unfortunately presents no comparable peaks.

Box 1

The gathering storm?

Excerpts from the US National Academy of Sciences report *Rising Above the Gathering Storm*:

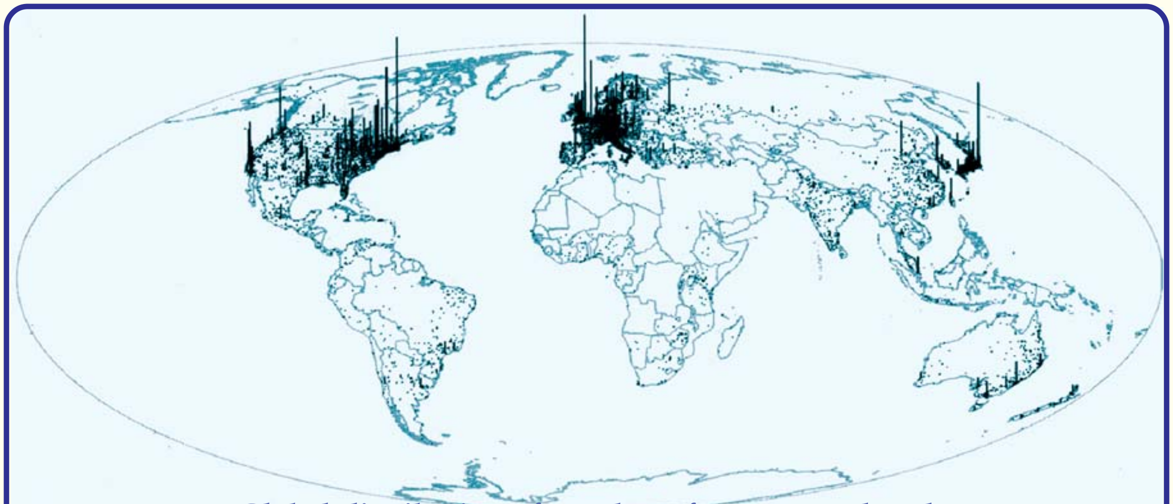
♦ Economic studies conducted even before the information-technology revolution have shown that as much as 85% of measured growth in US income per capita was due to technological change.

♦ Thanks to globalization, driven by modern communications and other advances, workers in virtually every sector must now face competitors who live just a mouse-click away in Ireland, Finland, China, India, or dozens of other nations whose economies are growing.

♦ [We] are worried about the future prosperity of the United States…. Great minds and ideas exist throughout the world. We fear the abruptness with which a lead in science and technology can be lost – and the difficulty of recovering a lead once lost . . .

The recommendations of the NAS Committee focused on four issues: K-12 education, research, higher education and economic policy.

From a recent survey (*Nature* 2004)[1] of impact-making scientific publications, we are 22 in global ranking – below China, South Korea and Poland. Indeed India's *relative* position in the world of science has declined in the last twenty years. We produce more science than before, but several more ambitious countries like China and S. Korea have outpaced us. The fraction of GDP that is spent on R&D has remained stagnant in India for two decades now (Graphic 2), whereas the more dynamic Asian countries have surpassed us in this period.



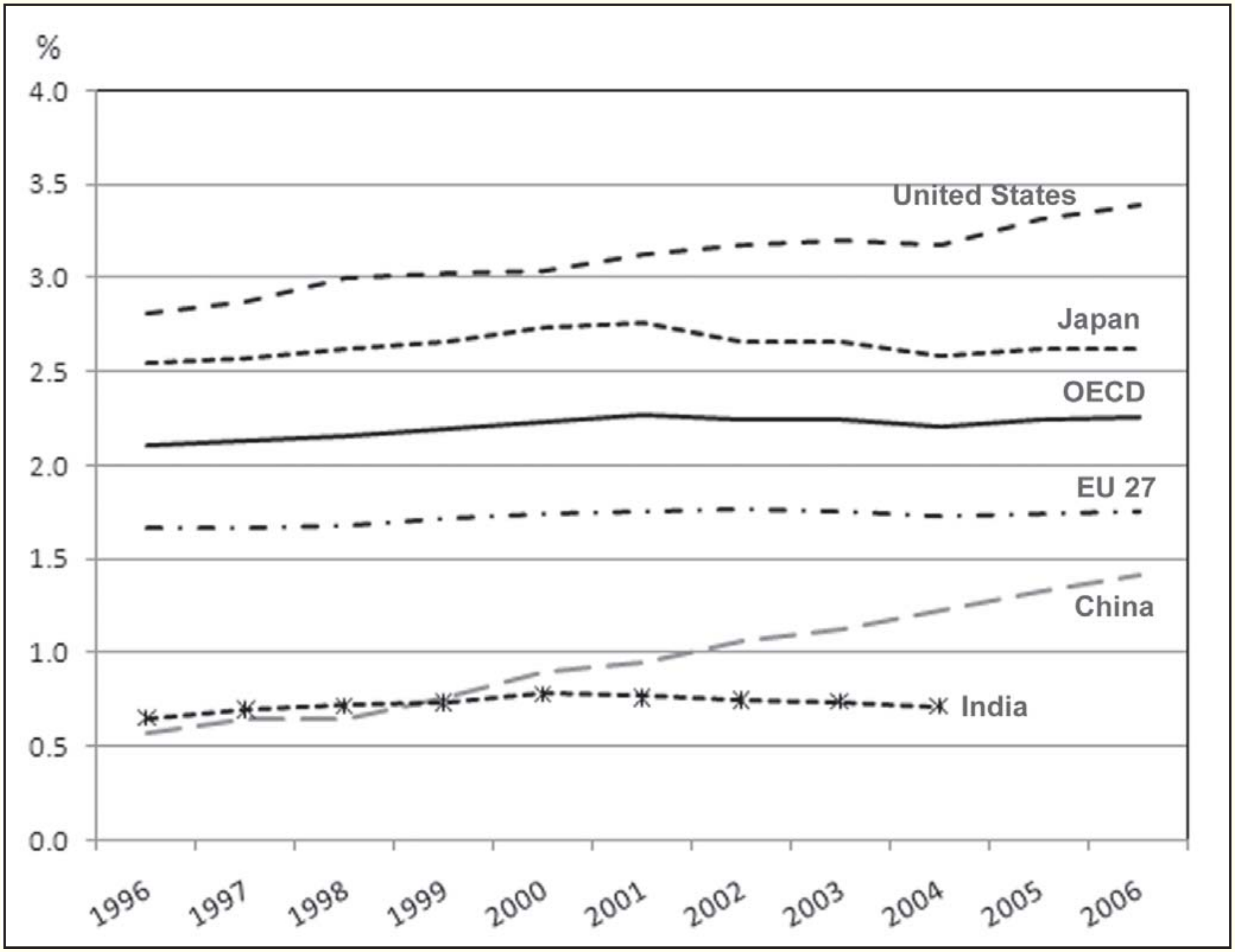
Global distribution of number of papers produced

Graphic 1: The Geography of World Science[2]

Two-thirds of the national R&D expenditure in India comes from the central government, and a quarter from industry. In contrast, it is almost the other way in S. Korea: about 30% of its R & D budget (about 3 ½ % of GNP), comes from the Korean government – which spends about the same on R & D as the Indian government does – but all the rest of it comes from industry. Indian industry is spending more on R & D now than before in absolute terms, but less relative to GNP (0.38% of GNP in 85-86, 0.2% currently). Except in sectors like pharmaceuticals and drugs, our industry does not appear to be making major investments in or demands on Indian science.

Yet, there are good reasons why India's presence in the world of science cannot be ignored.

Graphic 2: Gross domestic expenditure on R & D by area, 1996 - 2006 as a percentage of GDP[3]



OUR VAST BUT UNREALIZED POTENTIAL

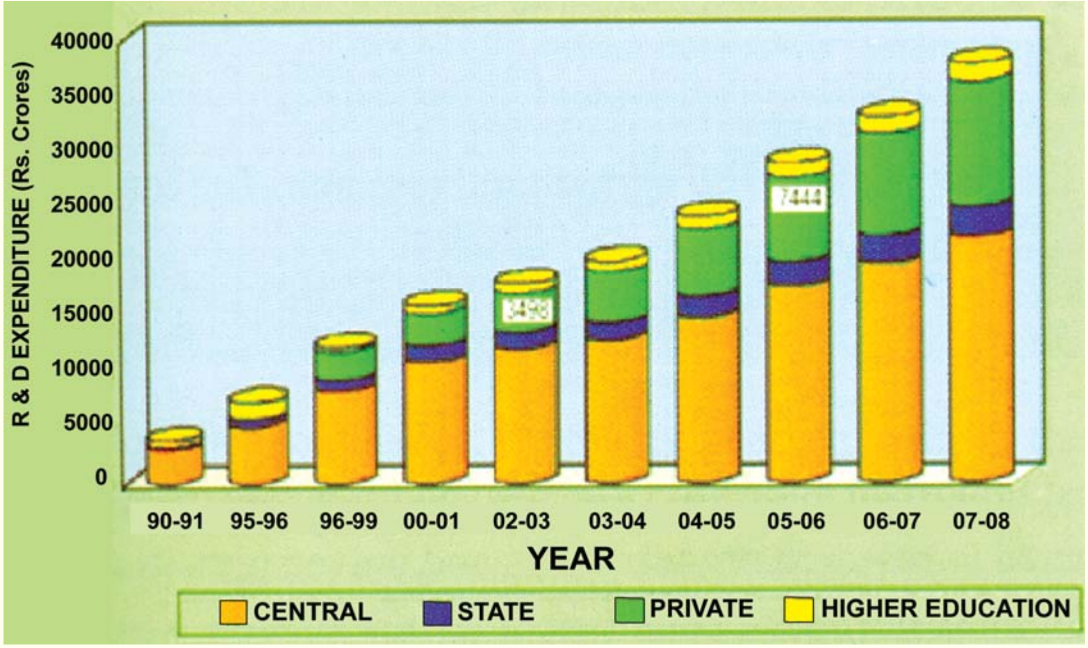
The untapped scientific and technical knowledge available to India for the taking is the economic equivalent of the untapped continent that was available to the US 150 years ago.

Milton Friedman, 1955 Report to the Union Finance Minister

India's Strengths

India's resources and strengths in science are considerable, but the potential is still far from realization. The rapid economic growth of the last fifteen years makes it feasible for the country to invest a great deal more in science than it could earlier. Contribution to Research & Development (R & D) from private sources is on the increase even though it still remains relatively small (Graphic 3). We believe, therefore, that the present time is a special one in the history of India's science as it offers an unusual opportunity to move towards a new and higher level than the one that we have become used to for decades.

At the school-leaving level there is great enthusiasm for science. A national science survey[4] has found that the most popular subject among tenth standard students is mathematics (with a vote of 35%). In the international Olympiads, Indian students have been in the same class as USA, South Korea, China and Japan in terms of medals won in mathematics[5]; in biology, they rank above the US. However, as these bright young minds begin choosing their careers they prefer other options, chiefly because they see science as offering fewer opportunities.



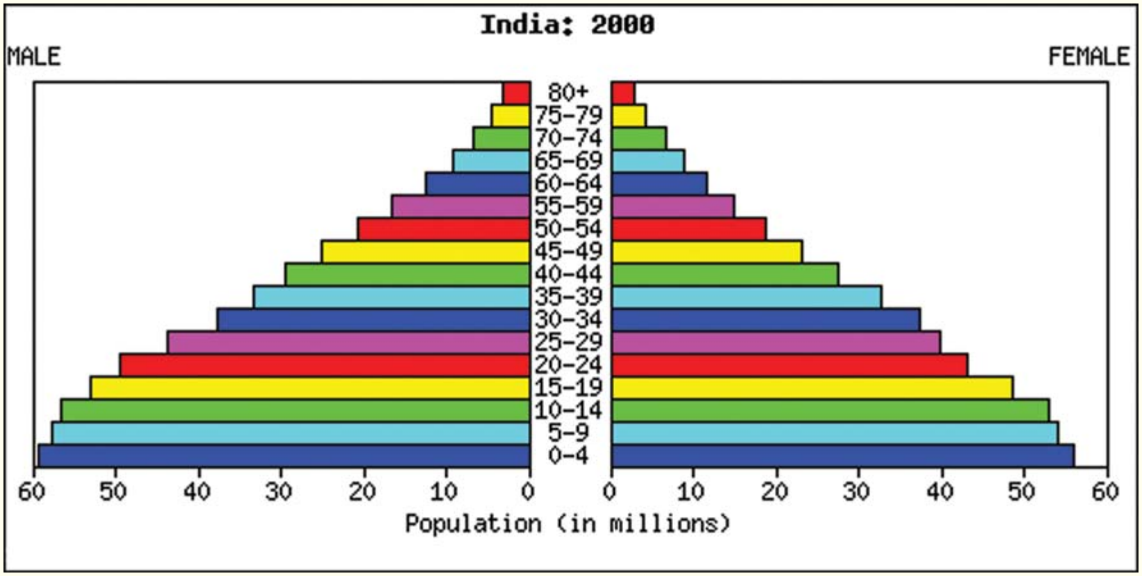
Graphic 3: Growth in Indian science budget

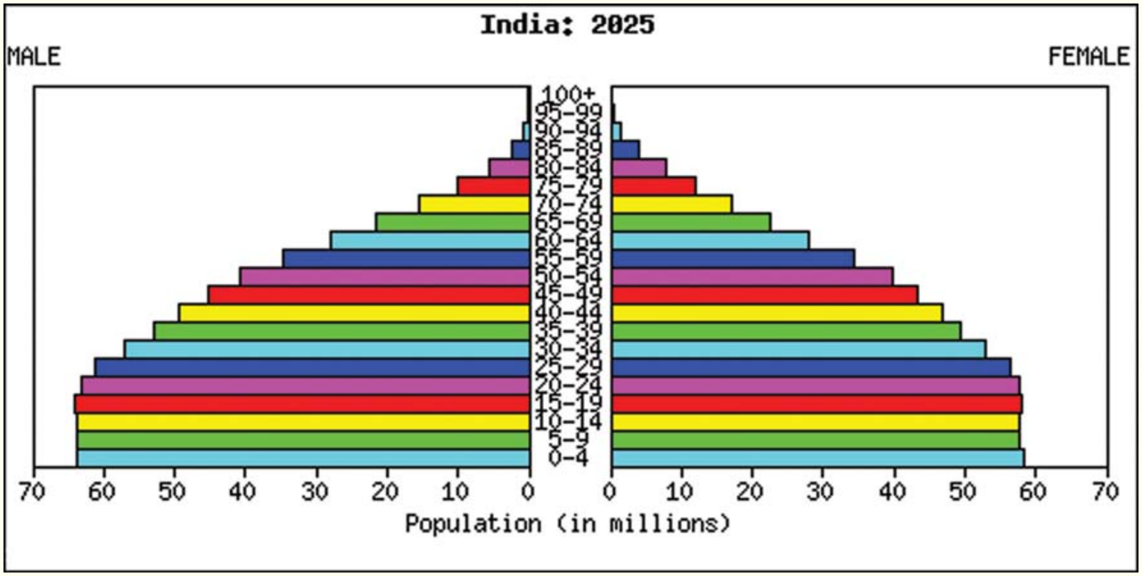
R&D expenditure[5]

India has several natural advantages as well. A major one is the youthfulness of India's population (Graphic 4), -which currently has a median age of 25 years. The number of Indians in the university-going age group (between the ages of 17 to 21) is currently about 9 crores (90 million), and will be 10 crores or more in 2025: the demographics will still be dominated by youth (Graphic 4). Only 13% are enrolled in higher education today. There is therefore vast scope for expansion.

India's strengths in original research in basic science have been substantial. The science, done in India, has often led to striking new technologies, but these technologies have generally been developed elsewhere in the world. We believe that this is a consequence of the overall weakness of the innovation ecosystem in India, as we shall discuss later in this report.

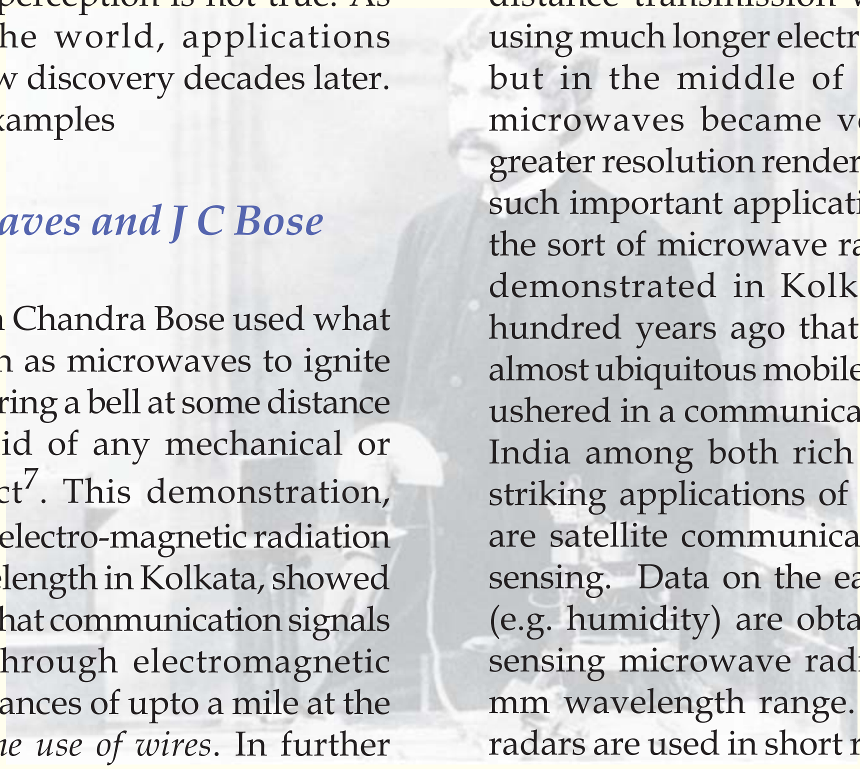
Graphic 4: Age-wise population distribution[6]





Indian basic science has spawned new technologies - but not in India

There is a fairly widespread perception that basic science done in India is not relevant for technology. The history of Indian science shows that this perception is not true. As elsewhere in the world, applications sometimes follow discovery decades later. Here are three examples



Millimetre waves and J C Bose

In 1895, Jagadish Chandra Bose used what are today known as microwaves to ignite gunpowder and ring a bell at some distance – without the aid of any mechanical or electrical contact[7]. This demonstration, carried out with electro-magnetic radiation of 5-25 mm wavelength in Kolkata, showed for the first time that communication signals could be sent through electromagnetic waves (over distances of upto a mile at the time), *without the use of wires*. In further demonstrations at the Royal Institution in London in 1897, Bose used waveguides, horn antennas, dielectric lenses and polarisers, and was the first in the world to use a semiconductor crystal (galena) as a detector of radio waves. In the years following, attention was focused on long distance transmission which demanded using much longer electromagnetic waves, but in the middle of the 20^{th} century microwaves became very relevant, for greater resolution rendered them central to such important applications as radar. It is the sort of microwave radiation that Bose demonstrated in Kolkata more than a hundred years ago that today drives the almost ubiquitous mobile phone, which has ushered in a communication revolution in India among both rich and poor. Other striking applications of millimetre waves are satellite communications and remote sensing. Data on the earth's atmosphere (e.g. humidity) are obtained by satellites sensing microwave radiation in the 1-30 mm wavelength range. Millimetre wave radars are used in short range applications on automobiles and at airports. Why did all these applications emerge in the West, not in India?

Raman scanners

C. V. Raman won the Nobel Prize in 1930 for the optical effect known after his name. Using condensed sunlight (the most intense source of illumination available to him at the time), Raman discovered a new kind of radiation, in which the scattered light had a different frequency from that of the illumination. Scattering changed the colours, so to speak. And the scatterers could be gases, vapours, liquids, crystals and amorphous solids. It turns out that the change in spectrum provides a unique identity tag to any type of molecule: i.e. gives it a 'finger-print'. Raman foresaw early that his discovery could have many applications. But it is only some 70 years after its discovery that Raman spectroscopy is beginning to directly affect the common man's life. This has become possible because of several other recent developments in technology: small, inexpensive and powerful lasers, fast digital image processing techniques developed for the space and communication industries, and surface-enhanced spectroscopy – all these have now combined to create a new 'Raman technology'. 'Raman scanners' using this technology have just reached the market place. With a hand-held device weighing less than 250g it is now possible to scan a surface non-intrusively and in real time to detect, to less than one part in a billion, traces of a wide variety of molecules – from pathogens and drugs to explosive chemicals. This technology appears set to grow vigorously in the next decade in a wide variety of fields – from health care to security to many others besides. So, the question is how and when do we build the ability to traverse the journey from the Raman Effect to the Raman scanner in our own country?

Mathematics and technology

The work of mathematical genius Ramanujan is a striking example of how basic research in such abstract branches of mathematics as number theory can have, many decades later, unexpected consequences and applications in new areas such as modern cryptography, population dynamics and theoretical physics. There are other examples (e.g. control theory, mobile communications) where basic research in mathematics done in splendid isolation has turned out to be crucial in some new technology. With the explosion of data and the advances in genomics, it is now widely agreed that newer areas of mathematics, in theoretical computer science, statistical analysis, information theory etc., need to be developed, as more scientific discoveries begin to be made through exploration of the vast quantities of data that modern technology provides us with. The paths of knowledge application and knowledge creation have clearly to combine to make rapid strides in development.

Many such examples can be given from other fields. What all of them show is that the journey from idea to product is complex, and demands science and technology developed in a variety of other fields for quite different applications, and a variety of expertise all the way from science to manufacture, financing and market knowledge. As we argue elsewhere, it demands a whole new ecosystem that encourages innovation.

THE NEW WAVE

Considering that India's potential in science and technology is immense, we believe that a policy of vigorous pursuit of science in the country can lead to rapid growth – of the kind that occurred in our GDP following the economic reforms of 1991.

The 1991 reforms have just now begun to touch the Indian science system. The revision of salaries by the Government of India in 2008 has been a significant step forward. The new Indian Institutes of Technology (IITs) established in recent years, the new system of Indian Institutes of Science Education and Research (IISERs), new universities being established in the country, new milestones in national mega-projects, the outstanding performance of a small number of state universities and the considerable growth in private wealth (in some cases arising out of the innovative initiatives taken by Indian industrialists and businessmen), all these are changing the scientific scenario in India dramatically. These strides should presage a new wave of investment and growth in Indian science – the only one of such magnitude after the early initiatives taken by the government led by Jawaharlal Nehru, in the late 40s and the 50s.

SCIENCE AT THE CORE OF NATIONAL DEVELOPMENT

What science should we do?

Curiosity and quest for understanding have driven human beings to discover many wonderful things. As we have already seen, it is virtually impossible to exactly predict how today's basic research will eventually improve our quality of life or to guess the new technologies or markets that may emerge. There is little doubt however, that such improvements and industries will eventually arise. The results of basic research are prerequisites for many future technological advances and societal benefits.

At the heart of the initiatives proposed here is the need to promote the pursuit of basic science in the country. Without the anchor of the strong foundation that basic research can provide, and the new ideas that can lead to future technologies that could be generated in the laboratories of the country, the vision of this document cannot be achieved. Tomorrow's technology often depends on today's basic science as exemplified earlier.

Innovative solutions will have to be encouraged, by establishing the whole ecosystem that is necessary for ideas that germinate in research centres to reach the market place. Indeed some of the work in the basic sciences should be driven by programs that the nation will have to undertake to tackle the major problems that the nation, and indeed the whole world, face (Box 2).

Advances in basic science will not by themselves make India a global knowledge power. It will be essential to identify the real causes behind our lack of progress in attaining food security, energy independence, efficient water management, tackling climate change, providing universal health care and a variety of other areas, some of which are global in nature (Box 2). From this point of view, it would be essential to incorporate a strong scientific component in education in socially important areas such as agriculture, medicine and veterinary science. We briefly indicate the kind of challenges faced by us in three areas, water, energy and food.

Box 2

Pressing problems of India

- Equity and social justice
- Universal access to education
- Energy independence
- Health-care for all
- Efficient water management
- Food security
- Mitigating effects of possible climate change
- Strengthening the innovation ecosystem
- Skill development for better employment opportunities
- National security, internal and external

The pressing problems that we face need complex, interdisciplinary solutions. None of them is easily solved, but there is no way that we will ever solve these problems without the proper use of science.

Water, Energy, Food

Among the foremost of these is water - in particular drinking water. Because of the vagaries of the monsoon, the nature of the hydrological cycle and the physiographical and geological attributes of the country the only replenishable water availability is finite and subject to unpredictable variability. Scientific analysis suggests that India's current water usage is already close to annual availability, and that this could lead to serious shortfalls over the next two decades. Furthermore, the physical and ecological integrity of India's water resource system is seriously jeopardized by rapid industrial and population growth. The time has come for India to formulate a coherent unifying policy that combines scientific knowledge with the need to ensure equitable sharing of a vital resource among all sections of society.

What are the principles that may govern such a water policy? In the first place, it must be realized that atmospheric water, surface water, soil water and ground water constitute a single interconnected resource. Management of such an interconnected resource is best achieved with drainage basins and ground water basins as the basic units. Resource integrity has to be preserved for future generations. It is time to realize that water use privilege cannot be granted to any person or institution in perpetuity. It is no longer possible for us to take water for granted as an abundant renewable resource. Yet, water is humankind's birthright - after all, the minimum that the state should provide every citizen is safe drinking water.

Formulating a rational water policy for the whole of the country is an enormously complex task. Nevertheless it is essential that effort be made that combines public education at all levels with the best scientific evidence and wide consultation with all stakeholders. The only way forward is to set up a water management system that is for the common benefit of the people and combines scientific analysis with considerations of social justice[8].

Energy shortage is a chronic and serious problem in many parts of the country. Uncertainties in the availability and pricing of oil resources, increasingly serious concerns with climate change, difficult ecological and human displacement problems with large dams, and a host of other similar considerations have made it essential for us to take a more integrated view of energy, in order to be able to secure it for our future. Our most abundant domestically accessible source of energy remains coal, but its use poses serious problems associated with emissions. Here, science and technology should be able to offer practical solutions, provided appropriate research and development programmes are pursued.

Energy at present is the core mandate of six Ministries: Power, Petroleum and Natural Gas, Coal, New and Renewable Energy, Environment and Forests, and the Department of Atomic Energy. A proper policy is clearly necessary for us to develop an appropriate energy economy that creates an optimal mix of energy sources capable of meeting the steeply increasing demands in the country. We have to become more involved in research in areas such as solar energy and hydrogen energy to fully benefit from the advances being made elsewhere, and to add to them from our own efforts. Even as we write this document, major new developments are being reported in these areas, and we should be pursuing relevant R&D with vigour and purpose.

If we consider the science of combustion and the need to enhance the efficiency of automotive or aero-engines, or for that matter the use of new fuels (such as bio-fuels) across the energy sector, so much can be meaningfully attempted and accomplished with the combined knowledge available in the different ministries. Much more has also to be done to develop more knowledgeable human resources in the energy sector.

Food security is associated with problems of water and energy resources that we have indicated above. Here again, science can play a major role, as it already did in the (first) green revolution. A second green revolution is now needed. In spite of all the controversies surrounding genetically modified foods, the science of genetics is bound to play a major role in these advances - as indeed it has done in the past.

In all these problems concerning the essentials of life - water, food, energy etc. - further progress will depend on the best use the country can make of evidence-based science, but its effectiveness will also depend on establishing new mechanisms of consultation, mutual education and dialogue among different disciplines as amongst various stake holders. Devising such mechanisms is essential if science is to be harnessed for the next phase of national development.

Science outside the science departments

Promoting the use of science and technology in various socio-economic sectors, outside the departments of science is of prime importance. With this objective, S & T Advisory Committees (STACs) in the socio-economic ministries were proposed to be set up during the Seventh Plan period. As a result, over the last two decades, 25 STACs and an Inter-sectoral S & T Advisory Committee with Secretary, DST as

Chairman have been established. The performance of most of the STACs does not present an edifying picture. It is understood that about half the STACs have not met even once during the last few years. It is not clear if any major programmes or projects have been taken to a stage where their impact has been felt in the economic growth of the concerned sector. However a few STACs that had distinguished scientists as Chairmen have yielded better results.

No coordination to achieve well-defined objectives from the use of S&T in a given economic sector appears to have been attempted.

Currently the science and technology components receive less than 1%, and in several ministries less than 0.5%, of the ministry's total allocation. The rate of increase of allocation to S & T is significantly lower than that of the total allocation to the ministries. Given the authority of the ministries, there is considerable room to derive support from industry, in the public as well as in the private sector, if collaborative projects can be thoughtfully crafted. Such measures can attract more investment in S & T from industry.

The scientific advisory system in the socio-economic ministries need to be restructured, in particular also to exploit the potential S&T strengths residing in national laboratories in several areas of considerable economic relevance.

A new mechanism must be evolved by the Prime Minister and the Cabinet to ensure that the STACs function smoothly and effectively, and that science plays its role in national development across different sectors.

INDIA AS A GLOBAL LEADER: THE WAY FORWARD

Making India a global leader in science

In order to begin to contribute significantly to world science and to make an impact on it, India's contribution to global scientific literature would have to rise to something like 10% (from the present 2% or so) – that is a major increase in ten years. Similarly our ownership of intellectual assets would also have to show an increase – from a little more than 1900 filed by Indians and sealed in 2007 to about 20000 patents sealed per year by 2020.

A mere increase in the number of publications or of patents, however striking, will not by itself make a great impact on India's position as a global leader. What is needed in addition is that, first, the science that is generated is of high quality, and second, it also helps in tackling the numerous problems of Indian society and state, and indeed of mankind as a whole, as already discussed. We must be able to afford the opportunity for all Indians to lead a life of dignity. These include such essentials as food security, water resources, energy independence, health care for all, a clean environment, universal access to education.

The country should get to be known for its excellence in science; in terms of metrics, the number of Indian publications among the top 1% of the most cited in the world would have to be higher than 5%. Some of our educational institutions should be amongst the top 50 in the world. Indian science products would have to be seen on the highways and sea lanes, in the skies, at home and everywhere in the global market place. India's natural advantage in knowledge-based industries must be fully exploited to generate novel solutions for old as well as new problems. To accomplish all this, pursuit of excellence has to become a way of life and only this can make us leaders in science, technology and innovation.

How can we begin to move towards achieving these goals? Given the young India advantage, one major instrument should be stronger science education at all levels, from elementary schools to post-graduate institutes, including a system of vocational training that can produce excellent technicians. At the early levels of education, the key to excellence in the education system is the teacher – as indeed it has always been in history and as our ancestors recognized all along (Box 3).

In technical education, a national or an international council could be appointed to restructure the present system and monitor its progress.

We will have to give considerable attention to provide massive continuing education programmes for teachers. Summer and winter schools (month or two long), retraining something like 50000 teachers each year over the next 5 years, are essential. We need to give teachers a position of honour in society – one from which teachers themselves encourage an open, creative questioning attitude. This involves permitting schools to adopt a wide variety of systems to suit the diversity of India's population, while at the same time ensuring quality – defined in a broad sense rather than as the mere ability to secure high marks in scholastic tests. The administration of the education system would have to take on a totally different character, drawing on all appropriate sources of funding and other support for establishing more schools. At the same time, given the inequities that have unfortunately been inherent in Indian society for far too long, a vast system of financial support to those in need or those who cannot afford appropriate education for economic reasons although they have the ability, will have to be created. The same private sector that has set up or promoted schools must be persuaded to support a vast system of new pan-Indian networks of assistance to the Indian young.

Similarly, in higher education, the vast expansion the country needs (Box 4) can only be achieved by public-private partnerships. We must recall that major investments in science education in the late 19th and the first half of the 20th century, were the result of private initiative. We should do everything to revive that spirit, including large tax benefits to private

Box 3

How to run the best schools in the world

The best school systems are not to be found in the countries which have done a great deal of research on education systems, nor in the ones who pay teachers the highest salaries, according to a report by McKinsey[9] The best-performing systems (as measured by the mean score in mathematics on an international assessment) are apparently in Finland, South Korea and Japan. What is common about them is that they have found ways to attract the best teachers to the profession. In South Korea, primary school teachers come from the top 5% of the graduating class in the 4-year undergraduate programmes undertaken in 12 selected universities. No more than the required number of teachers is taken every year. In countries like South Korea, Finland and Singapore the teaching profession is competitive, difficult to get into, and prestigious. Teachers undergo special training programmes every year. Failing pupils get attention, through separate programmes designed specifically for them.

No educational system can be better than the teachers it manages to get. This simple principle seems to be common to all the high-performing countries. In India, where teaching is unfortunately no longer a respected calling, we need to experiment with new methods of getting the best teachers into the profession and recognizing them for the profound national and societal value of teaching – and forming – new generations of citizens. The school system has to support all parts of the distribution – the high- and low-achieving tails and the mid-level groups. This needs a diversity in the system, but a method of preparing and rewarding the right teachers at each level remains the key ingredient of a successful system.

Space, communications and computer technologies should be fully exploited to provide best possible teaching across the country. The knowledge TV channels now running should be improved. Whatever else we may do, we should not forget that a main aim of our educational efforts should be to inculcate scientific temper amongst children and, indeed, all our citizens.

partners. It is equally important to take a major initiative in technical education, with special support for technology universities that can bridge the gaps between science and enterprise. Science must become an integral part of education in agriculture, medicine, pharmaceuticals, veterinary medicine etc., and in particular also in technology.

Box 4

How many scientists do we need?

In 2006-7, the total university enrollment in S&T (including medicine and agriculture) was 36.6 lakhs. The out-turn in 2003 was 6.1 lakhs, of which 82.6% took the first degree, 16.3% post-graduate degrees, and only 1.1% obtained a PhD. India graduated 8420 PhDs in science in the year 2005-06[10].

In the age group 17-21 years, the number enrolled in higher education in 2006-7 was about 1.1 crore, i.e. approximately 13%. Of these, S&T account for about a third – say 4 to 5 %. In 2025, the 17-21 year group will number around 9.8 crores. If we should plan for about twice the present ratio and require that 25% of them should be enrolled in higher education, we will have to cater to about 2.5 crore – nearly 2½ times the present number. This means a student body in S&T of nearly a crore, against the present number of about 37 lakhs. These are probably conservative estimates.

At higher educational levels, the numbers would have to increase a great deal more if India has to be competitive. In 2005-06, India produced about 1000 PhDs in engineering and technology, whereas the US and China were already producing about eight times as many in 2004-05. We should plan for a huge increase by 2030; even ten times would barely match China's current output. This shows the enormous magnitude of the problem. In areas such as computer science, the situation is serious, with only 25 or so Ph.Ds being produced per year in India.

During 2004-06, India produced one research scientist for every 7100 people; China 1 in 1080, S. Korea 1 in 240, Sweden 1 in 163.

Another way of looking at the problem is to plan for world-class education in all of S&T for 20% of the university-age Indians – i.e. to about 2 crores in 2025; If 10% of these went on to post-graduate work to embark on research (Masters + PhD – say over 4 years) we would have 20 lakhs – of which about 5 lakhs will graduate each year, say a tenth of these with a PhD (50000 approximately). At current ratios, about 35000 will be in natural science, and 5000 will be in engineering and technology.

No matter how we look at the numbers, if India has ambitions of becoming a leading global force in science, a massive increase in S&T education will be necessary – both in quality and quantity. We should expect the number of scientists to increase at least at the following rates by 2025:

Graduate scientists: 15 lakhs per year

Post-graduate scientists: 3 lakhs per year

PhDs: 30,000 per year

The large S & T manpower in India will not only support our national efforts but will also be able to assist the aging world elsewhere, making India a leading knowledge provider through its human resources.

It would indeed be advisable for a group of wise persons to examine the education scenario and manpower requirements of 2025.

It is not a question of numbers alone. We need to pick the best talent for science. This should be possible with the large untapped talent especially in rural India. Every effort should be made to attract young people in schools and colleges to science by taking various types of initiatives including setting up a large number of fully funded residential schools and colleges in India's interior. We should also use the talent of Indians settled elsewhere for various national endeavours and provide suitable opportunities for talented persons from other countries to work here. We should strive to make a scientific environment in India that is so attractive that many Indian scientists now working abroad will want to return and join in the exciting project of building a new India.

As much of the rest of the world grays into a predominantly older demographic profile India will only show a middle-aged bulge even in 2050, and will continue to possess a considerable human advantage.

Another advantage that India has is that it is today the most cost-effective source of internationally accepted R&D in the world. Roughly speaking, India spends only ½ % of what the world does on science, but produces 2-2½ % of global scientific literature (Table1).

Table1: Some S&T indicators for Select Countries[11]

Country	Total no. of publications (2006), (change over 1997)	High-impact publications % (change)	GDP, $ T(2003)	Investment R&D, %GPD	Investment R&D, $B	$ M/ publication	PhDs E&T per year
USA	451 028 (+18%)	63% (-4%)	10.9	2.68%	292.0	0.65	8000
UK	~122 000	12.8% (+25%)	1.79	1.89%	33.8	0.28	
China	78 671 (+358%)	0.99% (+125%)	1.42	1.31%	18.6	0.24	9000
South Korea	(+290%)	0.78% (+178%)	0.61	2.64%	16.1	0.60	
India	26 963 (+60%)	0.54% (+69%)	0.60	0.77%	4.6	0.17	700

Our total production of world R&D is small, but its cost-effectiveness is unsurpassed. Furthermore, public sector science in India, wherever it has been successful, confirms this advantage. For example, in comparison with that of the other major space powers, India has been described as running its 'prolific programme' on a 'shoestring budget' as *Aviation Week and Space Technology* has commented.

Although India is not yet a major source of innovation in the world, many Indian scientists (often working abroad) have shown that the innovative spirit is widespread among Indians. In a recent poll taken by Zogby International in the US 28% of 3000 respondents voted that the next Bill Gates will come from India: only the US (at 29%) had a better chance[12]. What India lacks is not the innovative spirit, but an effective innovation eco-system.

A framework for higher education

There have been numerous studies of the Indian higher education system, and several proposals have been and continue to be made to improve its performance. Successive Prime Ministers (beginning with Pandit Jawaharlal Nehru) have often remarked on the bureaucracy and political interference that characterize the system. As the problem has persisted in spite of all this attention, some radical ideas have to be considered. The following proposals are made, in the light of the Government's intention of establishing several world-class universities. As the present system is by common consent inimical to the success of such a project, a new framework has to be devised. Here are some criteria that would define a new framework.

- ★ Seek dynamic leadership at the top and provide "real" autonomy with minimal bureaucracy.
- ★ Get the best faculty and establish the best facilities
- ★ Establish a proper faculty promotion policy.
- ★ Keep out political interference
- ★ Welcome private investment and support from private wealth.
- ★ Assemble a diverse student body balancing excellence and inclusion.
- ★ Combine undergraduate teaching and world-class research

- Balance educational efforts in science, technology, humanities
- Inculcate national pride amongst pupils
- Build campuses with character and suitable traditions.
- Keep student numbers manageable
- Offer integrated 4+1 year BS/BA + MS/MA programmes with a flexible package of courses
- Match supply and demand

The innovation eco-system

In a world of rapidly-advancing and ever-changing technology, innovation is a key driver of science, technology and – indeed – of economic advance. Innovation is not just about patents and new products, though these are important outcomes of innovation. It is equally about new ideas, services, and even business models. Social networking sites like the Facebook are examples of new services based on technology, while Google represents an innovative business model (where the user does not pay for service).

India has been active in innovation of certain kinds. Its IT industry created a new and disruptive business model through its on-site plus off-shore structure, which resulted in unprecedented growth and success. The Tata Nano represents a combination of innovative design and engineering, while nano in a different sphere – shampoo and other sachets – has created a new business model serving what has been called the "bottom of the pyramid". This has been emulated in such vital areas as health. Grass-roots innovation thrives, as documented by the National Innovation Foundation. However, much of our innovation has been incremental and has focused on "jugaad", best characterized as improvisation rather than true or radical innovation. Inventions, break-throughs and large value-addition are rare.

The potential for innovation is extremely high since diversity and adversity, both crucial to innovation, are characteristic features of the Indian scene. The first permits, even encourages, out-of-box thinking, while the latter throws up day-to-day problems that can be overcome only by creative solutions. Our investments in higher education and R&D facilities should provide the wherewithal to facilitate innovation. In recognition of India's capabilities, a large number of MNCs have set up R&D centres in India. Yet India has not become a leader in innovation. (It is worrisome that 9 out of the top 10 entities receiving Indian patents are of foreign origin) What seems to be lacking is the overall eco-system that can translate the undoubted Indian potential into reality. The main elements of such an eco-system would include the following:

- Venture funding: While there is now funding available for commercial scaling-up of successful proof-of-concepts or pilots, there is yet a problem with regard to seed or "angel" funding that is willing to take risks on ideas. At this stage, failure rates are necessarily high and in many countries such funding is often provided directly or indirectly by government (Israel is a striking example). However, in the case of government involvement, there must be high failure-tolerance: conventional auditing, that tries to fix accountability for unsuccessful investments, will not do, as some failures are an integral part of innovation. A separate, large fund (of the order of Rs. 1000 crore/year) must be set up and administered autonomously– possibly through a public-private Board, or as a not-for-profit company that invests in innovative start-up ventures.

- Tax incentives: Given high failure rates, there must be some tax write-off and other incentives to encourage angel investing, linked to the crucial element of mentoring.

- Greater funding for new ideas and innovation in government-funded R&D organizations, academic institutions and universities, and a willingness to risk failure: Such funding could be separately provided (as extra-budgetary grants) through the fund mentioned earlier.

- Less bureaucratic controls in government-funded R&D organizations: This is a big impediment to free thinking, experimentation and innovation.

- Encouragement: Through both sabbatical leave and other schemes and appropriate funding, scientists and technologists should be encouraged to realize and monetize their ideas through commercial ventures.

- Changes in education curricula to encourage creative thinking and innovation (as opposed to rote learning): Since a great deal of innovation takes place through cross-fertilization of ideas, we need to encourage trans-disciplinary centres and give freedom to students to take various combinations of courses (as against the present strait-jacketing).

- A fund (either as part of the one suggested earlier or separately) to promote social innovations: Ideas or ventures that may not be commercially profitable but have high social returns will have to be supported.
- Encouraging tie-ups between academia, R&D laboratories and commercial ventures: This, as proven elsewhere in the world, is an excellent combination for promoting innovation and taking it to market quickly.
- Strengthening the intellectual property laws and their enforcement: While there are strong arguments for putting certain kinds of developments in the public sphere, there is also need to enforce IP laws, so as to encourage investments in and development of new products and processes.
- A special package for a Small Business Initiative that will promote the establishment of and provide support for small R &D intensive firms.

India needs innovation to tackle the diverse problems confronting it, including the one for converting our knowledge-assets to economic growth and strength. Fortunately the country has great potential to be truly innovative. Demography, democracy and diversity give us a unique advantage. If we can create the right ambience through an appropriate eco-system, we can reap the benefits of these advantages.

Finally, the investment in science that began some sixty years ago has left the country with a broad infrastructure going all the way from a few excellent academic institutions to fine research laboratories and effective technology delivery systems. This infrastructure has many weaknesses, but with the growing economic strength of the country a rapid build up has become feasible.

Investment in science

Science budgets of the Government have been steadily increasing, although as a fraction of GNP they have remained more or less stagnant in the last ten years (See Graphic 2).

The State Governments do not invest much money on science either. Only in some special sectors such as pharma have significant budgets been set apart for R&D

by industry. India is still a small player in high technology exports (Box 5), and the new wave in science that we advocate here would not be sustainable unless the demands made by not only the science sector itself but also by industry and commerce for scientist-personnel show significant increase. In recent years the nature of exports from India has been changing, and high-tech products are beginning to show a rise although the total still remains small. But there is promise that this can increase a great deal more. For example the Indian automobile industry surpassed the performance of China last year; the main force that drove this development was the higher skill levels of the Indian industrial work force[13]. Indian satellites continue to be 25-30% less expensive than those launched from western nations. With appropriate incentives for innovation and high technology exports, Indian industry will be well set to grow in internationally competitive sectors.

Box5

High-tech exports

The European Union's definition of high technology includes nine sectors: aerospace, computers and office machines, electronics and telecommunications, pharmacy, scientific instruments, selected electrical machinery, selected chemicals, selected non-electrical machinery and armaments. Over the period 1995 to 2006 India's high tech trade increased more than four fold (from US $ 1.0 B to 4.5 B), but over the same period Brazil's went up by 8 times and China's 25 times (to about US $ 300 B).

High-tech trade accounted for only 0.49% of India's GNP in 2006, and for 0.23% of global high-tech trade. India's imports of high tech goods increased form $ 2.6 B in 1995 to $ 23 B in 2006 – still only 1.2% of global imports. These figures are disproportionately low (the lowest in the BRIC countries), and explain the generally low demand for science in Indian industry: we are still largely a low-tech trading nation[14].

In such cases, government schemes must provide the full funding where necessary (for example in energy research and development, with specific goals over a 5-10 year period). Formulation of economic policies that reward competitive knowledge-intensive industries should receive high priority.

To make sustainable growth in science possible, it is necessary that it is perceived as a national goal, cutting across the various ministries of the Government of India, the public and private sector industry, educational institutions, national research laboratories and the growing private initiatives in R&D. This will need to be signalled through a variety of actions. First of all, the investment of the Union Government in science must begin to show a significant increase as a percentage of GNP, rising to at least 2.5% by 2020. States should also invest more in science as well as higher education and support their own universities adequately.

A special economic package must be put together for the promotion of high-tech industry in India and its exports (just as in the IT sector). Educational and research institutions in the country would have to go more global and make special schemes for exchange of scientists at various levels with selected partner nations or institutions across the globe. In particular, we suggest a major initiative that makes international collaboration both ways easier. It is necessary to devise special schemes for post-doctoral fellows and other professionals, both Indian and foreign, that make it attractive to work here. It should be noted that post-doctoral fellows have been largely responsible for the greater productivity in top class science in the advanced nations of the world; in India, a recent initiative makes post-doctoral fellowships more attractive, but a great deal more needs to be done. A scheme that will make it possible for increasing numbers of young foreign scientific workers to conduct collaborative research with Indian colleagues in our own laboratories can be a major step forward in enhancing the quality of communication and cooperation between the scientific communities of India and other countries of the world.

Can NSERB be an engine of change?

The recently established National Science and Engineering Research Board (NSERB), which is the Indian counterpart of the U.S. National Science Foundation, can act as an engine driving some of the changes. The Board should constantly monitor the state of health of Indian science, and take action on its own initiative to promote the growth of science and to realize the vision that this document sets out. It will be necessary to see that all serious scientists in India get adequate support for their professional work. It is also necessary that NSERB takes the initiative in putting together mega-projects or mounting grand challenges that will bring together scientists and their institutions from across the country, and perhaps the rest of the world, in achieving these objectives. One mechanism that might be particularly useful is to set apart funding for projects executed by teams of scientists cutting across disciplines and institutions, assembled together by enterprising scientists in the country. NSERB could also create new types of fellowships and professorships to support and encourage outstanding scientists of all age groups.

THE INDIVIDUAL AND THE INSTITUTION

The growth of modern science and technology in India owes a great deal to visionary individuals who went on to build great institutions. Beginning with the Indian Association for the Cultivation of Science set up in 1876 by a well-known physician of Calcutta, Dr. Mahendra Lal Sircar, the Indian Institute of Science established in 1909 by the vision of the great industrialist Jamsetji Tata, and the Banaras Hindu University in 1916 by Pt. Madan Mohan Malaviya, private initiative played a key role in reviving Indian science at a time when the national scene looked extremely bleak. Sir M.Visvesvaraya was the greatest national champion of modern Indian industry in the first half of the 20th century. Many of these pioneers encouraged public-private partnerships, of which the most striking example was the Indian Institute of Science, which came up by a three-party agreement between the House of Tatas, the Maharaja of Mysore and the British government. The Tata Institute of Fundamental Research has had similar origins, and was the result of the shared vision of H. J. Bhabha and J. R. D. Tata. There are numerous less well-known examples in the form of professional colleges built by successful local professionals or princes. In 1942, Indian private enterprise came forward to fund the Board of Scientific and Industrial Research when the British Indian government cut budgets because of the War [15].

Has this private passion for the growth of Indian science waned in the last sixty years? Since the economic reforms of 1991, private wealth in India has soared, but it is generally conspicuous by its absence on Indian campuses barring professional undergraduate courses. Indian business is now more entrepreneurial than ever. It has built the most competitive automotive and software businesses in the world, created the largest telecommunication market in the world, and a vigorous pharmaceutical industry. It also has the world's largest petroleum refinery. An Indian-born businessman has brought into being the largest steel-making entity in the world. The public sector has remarkable examples as well: one of the most cost-effective space programmes, and a science base that is the source of world-level R&D for most major multinational companies. The spectacular growth of private engineering and medical colleges, the former producing more than 10 times the graduates that government institutions do, indicate the potential of private enterprise in education.

Is post-reform private wealth allergic to major investments and initiatives in education? Does the present educational system, dominated by the Government since 1947, discourage bold new individual initiatives through over-regulation? Are there sufficient domestic incentives for such public-spirited initiatives? Is the United States doing better in inviting Indian wealth to *their* campuses than we are able to do ourselves here in India? These are important issues that need to be debated. We need to understand why private wealth has turned away from supporting excellence in higher education.

A WAY TO GET GOOD ADVICE

Many problems today, typified by climate change, genetically modified foods and water resources management, to mention only a few, touch the daily lives of all Indians directly. The problems raised here are complex. They have widespread social and economic impact, and often become subjects of intense political debate. While science must continue to seek advances on the basis of its own internal drives and judgements, a serious problem will remain in communicating the conclusions of science, simply and accurately, to the public at large. This requires a special effort. On controversial scientific issues (for example, genetically modified foods and climate change), the Government should make a serious effort to get the most unbiased and accurate advice possible by calling on the academies of science to present accurate accounts of the state of the art. It is worth considering whether this objective could be better achieved through a council such as the Science Advisory Council to the Prime Minister or by the constitution of a National S&T Council (NSTC), on the lines of the US National Research Council. NSTC would comprise all the major academies of science, engineering, agriculture and medicine, heads of science agencies and eminent scientists in their individual capacity. Such a council will be assigned the responsibility for major scientific assessments by commissioning reports through well-defined contracts and for advising the government on relative priorities in S&T and associated investments.

LIBERATING SCIENCE FROM BUREAUCRACY

Prime Minister Manmohan Singh stated in the recent science congress session that it is high time that we liberate science from bureaucracy. How true! Practice of science in India has been severely hampered by oppressive bureaucratic practices and inflexible administrative and financial controls. One of the necessary conditions for progress in science is the elimination or minimization of bureaucracy. This is required in the central government and even more so in the state governments.

In addition to eliminating bureaucracy, it is important that we restructure many of our organizations and institutions so that they are able to create the right atmosphere to pursue research and higher education more effectively. Restructuring is specially essential in the state university system and its educational institutions, where there is need for much better methods of appointing vice-chancellors, greater autonomy, major changes in the examination system, procedures for admission, recruitment and promotion of faculty, research administration and, in fact, a total transformation of the academic environment. We suggest that the Government appoint a Science Administrative Reforms Commission, comprising largely of scientists, to propose a new administrative system for universities, national laboratories and the science departments and agencies.

When asked about how to build a great institution, James Conant of Harvard University said the following: ***"Get the best minds and leave them alone"***. There is a lesson for all of us in this statement.

EPILOGUE

What has been projected here has to be accomplished within a short period, if India has to truly find a place in the sun; we cannot afford to lose time. The nation is demanding accelerated, inclusive growth and world class governance. Indian science is today in a position to help in this endeavour. India has to become a leader in the scientific world, and a knowledge provider for the world. For this to happen, it is essential that science gets an important position in our way of thinking. Pursuit of excellence and elimination of mediocrity should become guiding principles in all our endeavours. Policy makers, administrators, and politicians as well as the general public have to view science as an essential agent of transformation. There is much to be done by individual scientists, scientific institutions, academies, universities and the society at large. One hopes that the entire nation will rise to the occasion.

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"The key to national prosperity, apart from the spirit of the people, lies in the modern age, in the effective combination of three factors, technology, raw materials and capital, of which the first is perhaps the most important, since the creation and adoption of new scientific techniques can, in fact, make up for a deficiency in natural resources, and reduce the demands on capital. But technology can only grow out of the study of science and its applications.

The dominating feature of the contemporary world is the intense cultivation of science on a large scale, and its application to meet a country's requirements. It is this, which, for the first time in man's history, has given to the common man in countries advanced in science, a standard of living and social and cultural amenities, which were once confined to a very small privileged minority of the population. Science has led to the growth and diffusion of culture to an extent never possible before. It has not only radically altered man's material environment, but, what is of still deeper significance, it has provided new tools of thought and has extended man's mental horizon. It has thus influenced even the basic values of life, and given to civilization a new vitality and a new dynamism".

From the Scientific Policy Resolution (1958)

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