Oration 13:
2009 K.R. Narayanan Oration

Message from the President of the Republic of India

I am happy to learn that the Australia South Asia Research Centre (ASARC) is organising the 13th K.R. Narayanan Oration on the theme 'Rocket Science, Other Science: A Trajectory of Indian Science and Technology from 20th to the 21st Century' at The Australian National University, Canberra on 2 November 2009.

Since independence, Indian scientists have made noteworthy achievements in the field of science and technology, especially in successfully developed launch technology and launch vehicles. I hope that the oration will highlight the ways in which science and technology can be used for development of society.

I wish the oration all success.

Pratibha Patil
New Delhi
23 October 2009

Rocket Science, Other Science: A Trajectory of Indian Science and Technology from the 20th to the 21st Century

Roddam Narasimha

> The untapped resource of technical and scientific knowledge available in India for the taking is the economic equivalent of the untapped continent available to USA 150 years ago.[1]

I feel greatly honoured at having been invited to present the 2009 K.R. Narayanan Oration at this renowned university. Shri Narayanan was a person that I came to know, and quickly learned to respect, especially during the period (1986–89) that he was union minister for Science and Technology in Delhi — a period that started shortly after my own tenure at the National Aerospace Laboratories (NAL) began at Bangalore. It was both a pleasure and a privilege to have a minister of Shri Narayanan's erudition, with keen appreciation of the role that science and technology (S&T) could play in India's development, and a regard and sense of friendship that he and the scientific community shared with each other. When, in 1986, NAL embarked on a parallel computing project, Shri Narayanan was one of the closest friends and supporters we had. This friendship continued even after he became president of the Republic, and I have the fondest memories of his visits to the National Institute

1 Milton Friedman (1955), Report to the Union Ministry of Finance.

of Advanced Studies and the Jawaharlal Nehru Centre for Advanced Scientific Research, where he showed once again his warm and almost personal interest in the future of Indian S&T and the men and women who pursued science in India.

It is a privilege, therefore, for me to be able to pay a tribute to a great diplomat, scholar, gentleman and friend of science, and I am grateful to my hosts at the Australia–India Council and the Australia South Asia Research Centre at The Australian National University (ANU) for providing me an opportunity to do so.

It seems appropriate to use this occasion to sketch a personal view of the path that India has followed in S&T since 1947, the year that signalled the end of British rule, although (as I shall argue briefly later) the roots of national policy in this period are intimately connected with developments in Indian science in the first half of the 20th century. This lecture, however, is not intended to be a comprehensive survey of all the significant developments that took place during this period. Some of them have already formed the theme of previous Narayanan orations. Instead, I shall describe the path that has been followed in areas in which I have myself been involved in some way, in particular aerospace and computer technologies.

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Let me begin with space. The first, and indeed the most remarkable, aspect of India's space program is how long ago it started. The Indian National Committee on Space Research was established in 1962 as a part of the Department of Atomic Energy by Homi Bhabha, with Vikram Sarabhai as the committee's chairman. I shall return to the great impact that these two leaders have had on Indian S&T in the last half-century, but let me only note here a Bangalore connection. The speed with which space research was made part of the national agenda was perhaps in part due to the visions that Bhabha and Sarabhai shared on the way to build S&T in India. Both had been at the Physics Department of the Indian Institute of Science during the war years — Bhabha having been prevented from resuming his career at Cambridge by the war, and Sarabhai having been forced to wait to go to Cambridge to complete his doctoral degree. As Amrita Shah says in her fine biography of Vikram Sarabhai:

> It is tempting to speculate that Vikram and Bhabha, the two princes of Indian science, used their youthful days in Bangalore to spin dreams for the future … sharing their precocious hopes in the rambling wild landscape of the IISc or sealing a blood pact under the bright lights of the West End [Hotel] … because of the uncanny sureness with which they set about their plans and the suggestion of complicity in so many of their actions.[2]

The modest National Committee set up in 1962 was eventually to lead to what is probably India's most striking technology development program today.

Vikram Sarabhai came from a well-known and wealthy family of businessmen and industrialists in Gujarat, but chose science as his career. When he first invited me in 1964 for a personal discussion at Trivandrum, two things struck me. The first was the dramatic Nike–Apache launch from the beautiful, unspoiled palm-fringed beaches near Veli Hill. And the second was the company that Sarabhai was travelling with. It included not only some of the engineers and scientists who were then working with him, and a group of distinguished foreign scientists, but also artists, journalists and various other friends. Sarabhai asserted that India was not doing space for prestige, and, like the good businessman he was, insisted that sound economic evaluation of the required resources was necessary before embarking on the program. He also saw space science and technology as offering an opportunity for India to leapfrog from its backwardness and poverty. In the debate that still sometimes goes on between the virtues of leapfrogging vs those of piggybacking, Sarabhai (like most scientific leaders of his time in India) was definitely for leapfrogging. Having trained as a physicist who was used to balloons for cosmic ray work, it was natural for him to think of sounding rockets as providing another tool that would help his research. The first rockets launched in Trivandrum had to do with the upper atmosphere and the so-called electro-jet, a huge river of electric current that flows over the magnetic equator that lies across the southern tip of India.

Unfortunately, Sarabhai died when he was only 52. He was succeeded by Satish Dhawan, my own guru when I was a student at the Indian Institute of Science, and it was left to him to set up a space establishment in the country that would realise Sarabhai's dreams. In 1972, this establishment

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2 Amrita Shah (2007), *Vikram Sarabhai: A Life*, Penguin, New Delhi.

took shape in the form of a Space Commission (a high-level policymaking body) and a Department of Space (part of the government administrative machinery), which in another few years took charge of the Indian Space Research Organization (ISRO) (the technical executing arm) as well. In succeeding years, Dhawan went on to build the superb technology delivery system that ISRO has now become in India.

Dhawan vigorously and single-mindedly pursued the idea of using space technology for national development, and presided over a program that eventually led to a series of satellites for communication, meteorology, broadcasting, natural resource survey, education, and, more recently, cartography, ocean resources and health, etc. He showed his deep commitment to developmental goals by preserving space as an open, purely civilian organisation. In 1975–76, he used the US satellite ATS–6 for a Satellite Instructional Television Experiment (SITE), which broadcast a series of educational TV programs on such subjects as health, family planning and agriculture to more than 2,500 villages in the country — and in many different languages. For its time, SITE was seen as the largest societally motivated experiment ever conducted in the world using satellite technology.

Dhawan also was an unusual man. Even as he led big science he retained great respect for little science. He was keenly sensitive not only to social issues but also to environmental ones. So it was no wonder that he handled, in a most sensitive spirit, the displacement of the inhabitants (including the cattle!) of Sriharikota Island, which houses ISRO's satellite launch complex at what is now the Satish Dhawan Space Centre. He found birdwatching at the Sriharikota Range very relaxing and, even as he built and ran his space empire, made time to write a little gem of a book about bird flight. He spent much time charting the future of the space program in India, often with sketches and charts drawn in his own hand. And he realised that the program often called for unconventional methods.

The visionary commitment of these founding fathers slowly got translated into reality. On 19 April 1975, India's first satellite — called Aryabhata, after the great Indian astronomer-mathematician (fifth century CE) — was launched from the Soviet Union. On 18 April 1980, the Rohini satellite was launched by India's own launch vehicle SLV–3 from the Sriharikota Range. On 10 April 1982, the first Indian geostationary satellite INSAT–1A was launched from the US and, on 17 March 1988, the first Indian remote-sensing satellite IRS–1A followed. So, by the

1990s, the program was beginning to achieve the objects that it had set for itself. By 1997, India had launched eight satellites on its own rocket launch vehicles (and 12 more on others') by the time it could put its own automobile on the roads (India in 1998). So there *had* been some leapfrogging. With the more recent successes of the Polar Satellite Launch Vehicle (PSLV) and the geostationary launch vehicle (GSLV), the country now has what seems like a robust launch capability in satellites up to the 3–4-tonne class for geostationary orbits. India's entry into interplanetary exploration has been signalled by Chandrayaan 1, a remote-sensing lunar orbiter. Although prematurely terminated recently, it has acquired much new data on the lunar surface and, in particular, provided the strongest evidence yet of the presence of water on the moon. And the rest of the world is taking notice of these developments. The US magazine *Aviation Week and Space Technology* (*AWST*), the most widely read periodical in the field, has at various times run stories on India's 'prolific space program', called it 'world class' and pointed out that it is run on a 'shoestring budget' (currently of the order of about US$1 billion a year).

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To understand the early genesis of the Indian space program, we must appreciate that, in the India of the 1950s and 60s, there was widespread faith in the idea that modern S&T could solve many of the nation's old problems. Most Indian scientists believed this, and Jawaharlal Nehru, the first prime minister of the country, was a most eloquent and powerful advocate of the idea. Soon after the end of British rule, India set out (under Nehru's inspiration) on a spree of establishing new laboratories, agencies, industries and academic institutions. As Nehru happily laid one foundation stone after another, he confessed that he would much rather be the director of one of those laboratories, if he had the competence, than be the prime minister of the country. He advocated science with almost religious zeal. He saw dams, factories and laboratories as modern temples; and when he inaugurated the Indian Science Congress year after year, he would say that he had come to 'burn incense at the altar of science'. In 1958, he had parliament pass a Scientific Policy Resolution that declared government's determination to participate fully in the march of science, which Nehru called 'probably mankind's greatest enterprise today'.

Nehru's vision was that science and, in particular, what he called the scientific temper, was an instrument for nothing less than civilisational revival. This vision was shared by virtually all Indian scientists of that time. Among these the most dynamic and charismatic was Homi Bhabha (1909–66), who set up the country's atomic energy program — which, incidentally, became first the father of the country's space program (as we have already seen) and, later, a model for it when it became independent. Bhabha invented, with Nehru's encouragement, the administrative and scientific mechanisms that made it possible to pursue national science and technology goals in a focused way.

How was it that in 1947 Nehru and people like Bhabha could have had such extraordinary faith in the path of science, as well as the confidence that its pursuit would, first of all, be feasible and, secondly, successful? One part of the answer to these questions lies in Nehru's own unique educational background, for he studied natural science at Cambridge before his forays into law and politics. Even more important was the knowledge that, in the first half of the 20th century, a number of Indian scientists had begun to make such outstanding contributions as to attract attention all over the world. The remarkable thing about these scientists was that they were all nationalists in some sense — not in a jingoistic or xenophobic way, but rather as those intent on recovering lost civilisational pride. The most famous of these was C.V. Raman, who won the Nobel Prize for physics in 1930 (it is said that he had tears in his eyes when he had to sit under a Union Jack during the Nobel ceremonies). Then there was Meghnad Saha, who, through his well-known thermodynamic analysis of ionisation, was a pioneer in theoretical astrophysics; Satyendra Nath Bose, who invented quantum statistical mechanics even before quantum mechanics had been properly founded; and M. Visweswaraya, an engineer who promoted new industry as the *dewan* (chief minister) of the Maharaja of Mysore, and became India's most eloquent and passionate advocate for industry and technology, often crossing swords on these subjects with Mahatma Gandhi. Earlier, Jagadish Chandra Bose had made a microwave device that was the precursor of Marconi's radio. Then there was S. Ramanujan, the one least directly influenced by Western scientific thinking, but also the one to make the most striking impact on it by his vast outpouring of extraordinary mathematics. He was not just a much better mathematician than the rest, but (to borrow a description used by Mark Kac in another context) he was a magician. The methods he used to obtain his extraordinary results can only be ascribed to deeply rooted cultural instincts and weapons that he trained on modern mathematics, rather than on anything much he learnt directly from the West as method.

As I said, the confidence that people like Nehru and Bhabha had in the potential of Indian science was inspired by the knowledge that some Indian scientists had done outstandingly well against heavy odds. That faith was clearly shared by the well-known American economist Milton Friedman (Nobel Prize 1976), one of whose opening sentences in his 1955 report to the Union Finance Ministry provides the theme of this oration.

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It is useful to realise that Indian policy in many of its major technology programs has for long been based on what may be called the low-slow-steady approach. The funding in any given year may not be very high, but budgetary support has been steady, and the country showed that it had the patience to learn everything from scratch as a technology was painstakingly developed. This policy has paid rich dividends. We thus have not only a very good foundation but even an impressive superstructure in some of the fields in which the country has invested.

But times have changed. The economic reforms initiated in the early 1990s have, over the last 15 years, taken root. These reforms have been responsible for spectacular growth in many ways. From the point of view of a Bangalorean, IT and the software business come most immediately to mind. Growth in some of these areas cannot be attributed to direct government support or planning. They just prospered because of government's new economic policies. But as economic growth picks up pace in the country, time becomes a more important value than it was before. The need now is to make things faster and cheaper and hence to create wealth. So we should ask ourselves what set of policies we might now adopt that will do for the future what, 30–40 years ago, Sarabhai and Dhawan did for the present.

I would like to suggest that there are a couple of options that the country may be ready to examine. (I must emphasise at this point that I do not speak here as a member of the Space Commission.) First, in line with the changed economic thinking, we may ask ourselves whether a much more vigorous commercialisation of space is feasible and necessary. ISRO has done a commendable job of involving private industry in their programs. But should we do that in an even bigger way, so that the publicly supported space program can direct its manpower to taking a lead in things that private enterprise will not or cannot do? For example, by developing entirely new technologies, say reusable launch vehicles;

science and research such as the recent unmanned mission to the moon, Chandrayaan 1; or the proposed new satellites for astrophysical and atmospheric research (Astrosat and Megha-Tropiques, respectively).

The potential for the use of satellite technology in providing almost universal access to education is immense, but in spite of the recently launched Edusat, the potential is inadequately tapped in India. This is in fact strange from one point of view, because 40–50 per cent of the Indian population is still illiterate and, in many ways, satellite telecasts might provide an excellent medium for raising literacy levels, diffusing a variety of skills, and making the methods and the wisdom of the best teachers in the country available to huge numbers of people.

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I should mention in particular satellites for weather and climate research. The space program has already taken several initiatives in atmospheric and oceanic sciences. The INSAT series has provided imageries of the Earth in both visible and infrared parts of the electromagnetic spectrum, and offered communication channels for transmission of meteorological data. The geostationary satellite Kalpana, launched by PSLV, was meant exclusively for meteorological applications. Two Oceansats provide much data on the ocean surface, including sea-surface temperature and winds.

A major step forward will be taken in 2010 with the atmospheric research satellite Megha-Tropiques. As the name indicates ('Megha' is cloud in Sanskrit and 'Tropiques' is the tropics in French), the satellite is a collaborative effort between India and France devoted to the study of tropical convective systems. The tropics are driven by solar radiation and moist convection, so the satellite focuses on water cycle and energy budget issues in the tropical atmosphere, and will provide data over the tropical belt of approximately 30°S–30°N. A unique feature of the satellite is its repetitivity: the same tropical site is visited four to six times a day over the heart of the tropics, enabling valuable data to be acquired over the whole diurnal cycle.

The mission objectives are:

1. to collect a long-term set of measurements with good sampling and coverage over tropical latitudes, and to understand better the processes related to tropical convective systems and their life cycle

2. to improve the determination of atmospheric energy and water budget in the tropics on various time and space scales
3. to make detailed studies of special events like cyclones, floods, droughts, etc.
4. to carry out analyses that can improve forecasting skill on the monsoons
5. to provide to forecasting centres/groups real-time data that can be assimilated into operational or research models to enhance their performance.

The objectives are sought to be achieved through four payloads:

- MADRAS (microwave analysis and detection of rain and atmospheric structures)
- SAPHIR (sounder for atmospheric profiling of humidity)
- SCARAB (scanner for radiation budget)
- GPS radio occultation sensor (ROS).

MADRAS will provide data on rain above the oceans, integrated water vapour, liquid water in clouds, ice in cloud tops, etc.; SCARAB will provide short- and long-wave radiative fluxes; SAPHIR will provide humidity profiles; and the GPS ROS will provide temperature and water vapour profiles.

Megha-Tropiques promises to provide unique data sets. It follows TRMM (Tropical Rainfall Measuring Mission), the joint US–Japan tropical radar satellite, whose current life is set to end in 2010, and may well turn out to be the harbinger of the international Global Precipitation Mission, which envisages a whole constellation of satellites launched by several international partners.

The Megha-Tropiques will be launched from Sriharikota on ISRO's PSLV, and signals India's entry into joint international projects on earth science related issues using the best available space technology. The tropics are a frontier area of meteorology. The three major countries in the global tropical belt are India (approx. 8°N–36°N), Australia (approx. 11°S–39°S over the mainland) and Brazil (approx. 5°N–32°S). Given both the scientific challenge and the extraordinary relevance of the tropics to its own inhabitants and the rest of the world, more major international projects in the field are bound to contribute to the wellbeing of the planet.

Nearly half the land area and nearly half the population of the world live in the tropics. The tropics receive two-thirds of total world rainfall; they also receive relatively more solar radiation, and export the surplus to higher latitudes keeping them warmer than they would otherwise have been. Interestingly, meteorological connections exist between India and Australia, as foreseen in the 1920s by Sir Gilbert Walker who, as head of the India Meteorological Department, reported the significant correlation between rainfall in India and pressure at Port Darwin and south-east Australia, for example (envisaging what is today called ENSO, or the El Niño-Southern Oscillation phenomenon). Shouldn't India and Australia be working more closely in atmosphere–ocean science?

Such initiatives should become more feasible as the space program tends towards greater self-sustainability. Thanks to the progress achieved by Indian space scientists and technologists, that now no longer seems difficult to accomplish. Globalisation should make international projects more attractive, provided geopolitical considerations do not intrude. There is an excellent chance that such international ventures can in fact lead to both faster and cheaper projects and services for both collaborating parties. *AWST* talked about ISRO's shoestring budget; a study carried out at the Madras School of Economics[3] shows in specific cases how cost-effective the Indian program is. So we may need a two-pronged policy. On the one hand it could be more oriented to commerce and wealth creation (of which Sarabhai the scientist-businessman would surely have approved). Conversely, it could emphasise the vigorous use of satellites in education and scientific research (helping to enhance the value of our human resources), including in particular the earth system (of which Dhawan the humane technologist would have approved). This would still be part of the developmental process that ISRO's founding fathers placed before us. Commerce, basic science, education, land, water and the earth system as a whole can form a sustainable complex of goals.

These goals, in part new and in part only a new version of the original vision, can be pursued with confidence, because of the sustained achievements of the Indian space program in the last 40 years.

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3 U. Sankar (2007), *The Economics of India's Space Programme*, Oxford, New Delhi.

I would now like to consider computer technology, which has some interesting parallels with space but also some striking differences. In the 1980s, it started with the need felt in India for high performance computing systems on a variety of national projects. However, it was soon discovered that, because of the technology embargoes prevailing at the time, it was not possible to import any of the supercomputers of that era to India (the exception was a Cray machine that was acquired by the National Centre for Medium Range Weather Forecasting at Delhi for numerical weather prediction).

In the early 1980s, some scientists both in Europe and US had started experimenting with parallel computing (i.e. achieving higher computing speeds by using a large number of processors that would work in parallel). During the time that I was at NAL we began a parallel computing effort in a small way in 1986. To our (and everybody else's) pleasant surprise, my colleague at NAL, Dr U.N. Sinha, was able to put together, before the end of the year, a small parallel computer that was already faster than the large mainframe that NAL had been using at that time. The demonstration of the way that the Flosolver (as the NAL parallel computer was called) could solve, for example, the transonic small perturbation equations faster than the mainframe removed all scepticism on the possibility of using parallel computers for tackling problems in fluid dynamics. (By the way, that scepticism was shared at the time by many experts in the West as well, and so was not limited to Indian scientists.) Through the Scientific Advisory Committee to Prime Minister Rajiv Gandhi, a proposal was made to the government in 1986 for pursuing a major national initiative in parallel computing. As is well known, Mr Gandhi was a great advocate of computers in the country at the time, and I recall that the less than 10 minutes that had been allotted to me to make a presentation to the prime minister extended to 90 minutes — because of his extraordinary interest in the project. At the end, Mr Gandhi said that the question was not whether we should make parallel computers but how fast we could make them and at what cost. (He was also all for leapfrogging.) Very quickly thereafter several parallel computer projects were undertaken in the country. These had different philosophies, and it was decided that each of them was valid in its own way and should continue with further development. I must mention here that Mr K.R. Narayanan, as minister for Science and Technology at the time, was a great supporter of the Flosolver project, and he kept asking me years later (even after he had become president of the Republic) how the project was going. What started as a small effort to acquire some additional computing power has now gone through six generations (Mark 7 is now operational), and has led to new technology development and new architectures (some of them patented). All this has been done at low costs compared to international levels, and with huge and enthusiastic student participation.

But as these computers went from one generation to the next, the most important applications also slowly changed. Currently, modelling of the atmosphere and the oceans takes precedence over the other applications. Considerable commercial interest has been shown in the possibility of using these computers for financial modelling. A separate project, through a scheme called the National Millennium Initiative for Technology Leadership in India and conceived by the Council of Scientific and Industrial Research, has selected modelling monsoons as a targeted application. Forecasts are now being continuously made and sent to the India Meteorological Department for their use.

An interesting aspect of the parallel computing effort in India is that, over the years, four distinct groups emerged, including one at the Centre for Development of Advanced Computing at Pune whose machines, known as the Param series, have probably had the widest use in the country (some of them even exported). Nevertheless, none of these efforts can be called a strong commercial success. At the time that the projects were undertaken, commercialisation was not ignored, but it would be correct to say that non-vulnerability to technological embargoes was an even more important consideration. After all, the first objective of Mrs Gandhi's Technology Policy of 1983 was 'to attain technology competence and self-reliance to reduce vulnerability'. To that extent, the projects have been most successful. But, in spite of serious efforts, it has not been possible to get the involvement of private industry in the project, although it has often shown considerable interest. The question of forging stronger links between the laboratory and the marketplace is one of major interest and continuing importance in India even today.

A similar problem has also affected another computing initiative relating to what came to be known as the Simputer. The roots of this project can be traced to a meeting that was organised by the National Institute of Advanced Studies (NIAS) as part of the first Bangalore IT.COM show (as the series came be known later), held in 1998 with the support of the late Mr Sanjoy Dasgupta who conceived the idea. As part of the first event, NIAS organised an international seminar that considered the future of IT in developing countries. In keeping with the broad objectives of NIAS, which in particular emphasise the bringing together of people in science, technology, the humanities and a variety of other sectors including business, industry and the political leadership, we included in the NIAS team that organised this event both distinguished academic scientists like Professor Vijay Chandru of the Indian Institute of Science, industry experts like Mr Vinay Deshpande, sociologists like Professor M.N. Srinivas and others. In fact, a Bangalore Declaration was passed at the meeting and had the wide approval of both the developing and the developed countries whose representatives were present at the meeting.

That declaration highlighted a major concern at the time, which was what has been called the digital divide. In trying to see how the problem represented by the divide — that is, between those who have access to (for example) the internet and those who do not — the idea emerged that what India needed was a small handheld computer that could sell for a few thousand rupees (something less than $100). This led to the concept of the Simputer, which excited worldwide attention. The *New York Times* called it the most significant innovation in computing technology in 2003, *Time* magazine said it was 'one of ten technologies to know on the planet', and the MIT *Technology Review* rated it among the top 10 innovations of the year. Some examples of the Simputer were made, the product was officially released and something like a thousand test pieces were sold on a very special application — to the great satisfaction of its fastidious customer. Nevertheless, the Simputer did not become a commercial success.

In retrospect, it has become clear that it is not enough to have a brilliant idea; to convert idea into reality in the marketplace takes a variety of other resources, capabilities and skills that together constitute what may be called the innovation ecosystem. This ecosystem has technology and the technologists as one component, but includes financing, promotion, advertisement, large-scale applications, the ability to take risks and accept failures and, increasingly, a globalised business model. That ecosystem is not yet in place in India, especially for the technologist–entrepreneur. So, interestingly, at the time the Simputer was first made, it could not break into the market, for whatever reason; it now looks as if there may be a resurrection: it has acquired a second life as newer applications are making demands for which it appears a very appropriate solution.

But the Simputer is only one of the most well-known instances of a good idea that did not reach the market. There have been others that have had a similar experience. It is to be hoped that, as the country breeds more technologist–entrepreneurs, the rest of the ecosystem that is needed to convert such ideas into wealth will quickly emerge.

Meanwhile, a major commercial entry into the supercomputer market is represented by the computer Eka, which the Tata Computing Research Laboratories in Pune have designed and constructed. At the time that it was put into operation (in 2007), the Eka was the fourth most powerful computer in the world; it remains to this day the most powerful in Asia. It is being used for scientific research, technology development, weather prediction and a variety of other applications. It appears that this project works to a different business model. Here much of the system may carry imported components, but the basic concept, the financial risk involved in the project and the business model supporting it are all completely Indian. The fact that private industry in India is now willing to undertake such projects (either moving away from piggybacking to leapfrogging, or making a pragmatic mix of the two) marks a significant departure in the way that technology development can take place in India. The Eka appears more ambitious than the interesting developments in some other sectors, for example, pharmaceuticals. Nevertheless, the number of industries that are beginning to see the *economic* advantages of technology development within India is slowly on the rise. In support of this view we may also quote the recent example of what may be the world's cheapest car, namely the Nano. The interesting thing about both Eka and Nano is that they are primarily inspired by the needs of the Indian market, with the realisation that success achieved there may well take the product to other parts of the world.

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All these projects — whether in space or in computer technology — depend critically on management of the skills and knowledge 'available in India for the taking', as Friedman put it, and the world is slowly discovering this 'untapped' resource. If India has recently emerged as a major exporter of automobiles and automobile parts, it is because of the discovery that India offers cheap *skills* (rather than cheap labour). Several years ago, *Business Week* and a whole host of multinational corporations (led by GE) discovered similarly that India was about the most cost-effective location in the world for doing high-level R&D (research and development). India's scientific output, measured by the number of publications in well-recognised scientific journals, remains about the most cost-effective source of high-quality scientific research in the world. (But the total scientific output itself, although growing, remains stagnant at about 2.5 per cent of the global output.)[4]

We need stronger policies that recognise the natural advantage that India has in its youthful human resources, and provide all the supporting institutions and mechanisms — from education to counselling to encouraging technological entrepreneurship and domain scholarship — that can convert this untapped talent (the economic equivalent of the untapped American continent of the 19th century) into wealth and national wellbeing.

I have in this lecture tried to trace the way that science and technology have evolved in India in two sectors in which I have some direct personal experience. (I could have added others, like the aircraft industry, where the situation is quite different from its space cousin, but the overall conclusions would not change.) After the economic reforms of 1991, the rate of growth of the Indian economy has risen and has typically been in the range of 6–8 per cent in recent years. Business leaders are tackling more challenging and competitive technology-driven products and systems. The examples I have described show that there is plenty of talent in India to take on the most challenging tasks in modern technology (and that talent is not confined to the metropolitan centres and the national institutes: it is spread across the country). Both the public and the private sector have demonstrated this, especially in the last five to 10 years. This augurs well for the future. At the same time, we have instances where brilliant ideas have not made it to the marketplace. It is my personal view that the ecosystem that can make this happen — all those advanced services that include venture capital, market survey, globalised manufacturing, being first to the marketplace and many others — are not yet in place; it needs to be a part of national endeavour to correct the situation as early as possible. Something similar is true in the field of basic science as well: in spite of the many new initiatives taken to promote it, we are still a relatively small force in global science, and that relentless pursuit of excellence that leads to game-changing ideas has not yet become part of the Indian academic environment.

4 Roddam Narasimha (2008), Science, Technology and the Economy: An Indian Perspective, *Technology in Society*, 30(3–4): 330–8.

But things are changing rapidly, and we may expect further initiatives in coming years that will enable India to create systems that can tap its great human resources more effectively.

Thank you, once again, for inviting me to deliver the 2009 K.R. Narayanan Oration.

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