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Science, Technology, and Development

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NATIONAL INSTITUTE OF ADVANCED STUDIES
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SCIENCE, TECHNOLOGY And DEVELOPMENT

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Abstract

India, coming out of centuries of colonial rule seventy-five years ago, opted not just for a democratic form of governance but also for Science and Technology for development. Though India has been able to build considerable S&T strengths during these decades and has addressed many of its problems, the economy of the country continues to remain like that of a developing one. In contrast, China has been able to lift itself into the comity of developed nations in a span of two decades. We can argue that this has been made possible by China's increasing investments in higher education, research and development and technology-driven entrepreneurship. India's investments in these have been sub-critical as compared to developed countries, specifically China. India needs to augment these and as the Chinese experience has shown, the payback of these investments is rapid.

Preamble

February 28, 1928, is an important date in the history of Indian Science. It was on this day that a landmark discovery in modern physics, the Raman Effect, was published by an Indian scientist, Chandrasekhara Venkata Raman, who was working in India. The discovery earned Raman the Nobel Prize in Physics in 1930. Raman scattering (scattering of photons by matter), with its ability to explore molecular structures having extreme sensitivity in a non-destructive manner, makes it a very valuable tool in basic research and applications in industry.

Were there other important scientific discoveries from India that made India proud during those decades? Yes, of most definitely! One cannot forget the path-breaking contributions by J C Bose, S N Bose, Megh Nad Saha, and Srinivasa Ramanujam during these decades. Often called the Father of Radio Science, J C Bose invented

1 Report based on the National Science Day Lecture V S Ramamurthy on February 28, 2023, at Bhabha Atomic Research Centre, Mumbai.

wireless communication long before Guglielmo Marconi, who developed the first proper system of radiocommunication. He was also the first to use microwaves to study plant and animal tissues and their response to electric stimuli. Bose was deeply committed to scientific education and outreach. S.N.Bose's research is immortalised in the name bosons given to particles with integer spins and to the statistics they obey, namely "Bose-Einstein" statistics. He envisaged the spin of photons as one, which was confirmed in experiments by C V Raman and his colleagues. Megh Nad Saha's work on thermal ionisation laid the foundations of astrophysics and the quantitative study of star interiors. He also essentially envisaged the Compton Effect by explaining that the tails of comets point away from the Sun because of the pressure exerted by the Sun's radiation. Srinivas Ramanujan's contributions to number theory are unprecedented. Many of his theorems provide only the final results as he never bothered to write down their proofs. They continue to be studied even today, more than one hundred years after his death.

One cannot forget that those were times when India was still under colonial rule. State support for scientific research was nearly non-existent. Scientific research in the following decades saw an increasing role of sophisticated instruments such as computers, nuclear and particle accelerators, detector systems etc. for research, making research expensive and unaffordable for individuals and institutions without explicit state support. It is not surprising that scientific research in India could not remain globally competitive in the decades following World War II.

I
The India Story: Seventy-five Years of independent India

When India emerged as an independent nation on August 15, 1947, it had a population of nearly 340 million, with around 85% living in villages and deriving their livelihood directly or indirectly from agriculture. India's GDP was about Rs. 2.7 lakh crores, a mere 3 per cent of the global GDP. The literacy levels were low at around 12 per cent with only about 0.2-0.3 million students in 20 universities and 500 colleges spread across the country. Unlike other countries that came out of colonial rule at around the same time, independent India did not just choose democracy for governance but also Science and Technology for development. Of course, India had an advantage- it already had exposure to the English language and the Western educational system, in addition to a long tradition of science.

Unsurprisingly, education, scientific research, and technology for development were accorded the highest priorities in the national development plans of independent India.

The early start in strengthening education resulted in the strengthening of school and undergraduate education across the country. The literacy rate presently stands at about 78%, as India considerably expanded its education infrastructure. According to reports in 2021, India had 1.2 million primary schools, more than 150 thousand secondary schools, and about 140 thousand higher secondary schools, with more than 263 million students enrolled in Grades I to XII. In 1950, skill development was also introduced in the educational system to ensure a steady flow of skilled workers in different trades for the domestic industry. Through a network of about 15,000 Industrial Training Institutes spread across the country, about 2.7 million trainees are being trained every year in about 150 trades presently. However, it is estimated that India needs a factor of three or more skilled workers every year.

Before independence, postgraduate education and research were considered elitist- with very little state support. Recognising the increasing role of Science and Technology in shaping the twentieth century and beyond, India also chose to strengthen higher education in this field, and established several central and state universities, comprising Institutes of Technology, Institutes of Management, and recently, Institutes of Science Education and Research, and R&D institutions with focused mandates. It is reported that in 2021, India had more than 41 million students across roughly 11 hundred universities, 44 thousand colleges, and 11 thousand stand-alone institutions.

Two of the well-known success stories of the early decades in addressing national challenges using Science and Technology were the Green Revolution, which turned a country of acute food shortages into one of food surplus and security, the and the White Revolution which made India one of the largest producers of milk and dairy products in the world. India has also emerged as a leading producer of pulses, fruits, and vegetables.

Major industries in India before independence consisted mainly of textile and jute, both of which suffered greatly during partition since significant cotton and jute-producing regions of undivided India went to West and East Pakistan. The establishment of heavy industries was initiated during the Second (1956-1961) and Third (1961-66) Five-Year Plans, leading to the establishment of steel and fertiliser plants to make machine tools and heavy electrical equipment. Today the country is nearly self-sufficient in all heavy industry areas.

India was also largely dependent on imports of drugs and pharmaceuticals. Generic drugs and vaccines at affordable costs are fields where India has put an indelible footprint. It has been able to successfully eradicate smallpox and polio, and is making rapid progress in the elimination of tuberculosis. Aside from the developed areas of the world, India is one of the few countries that was able to develop an affordable vaccine for the COVID-19 pandemic, followed shortly by the creation of a nasal vaccine, the only one of its kind globally.

India’s foray into nuclear and space technologies is a unique story in itself. While the two technologies were still emerging and considered luxuries of the rich across the world, India recognized not only the true potential of these two technologies for developing countries like itself but also the need for trained human resources to implement the ambitious programmes.

Considering the large energy needs and limited energy resources, a Three Stage Nuclear Programme to make optimum use of India’s vast thorium resources was conceived and implemented. India has been designing, developing, and constructing nuclear reactors for decades now. It is one of the few countries to successfully implement a Closed Fuel Cycle to process and use spent nuclear fuel. There are currently 22 reactors having a total capacity of 6,780 MW that are operating, with plans to raise it to 22,480 MW by 2031. India has also been using nuclear techniques in diverse non-power applications such as nuclear medicine, agriculture and industrial applications, desalination of seawater, etc.

When India conducted the 1974 Peaceful Nuclear Experiment in Pokhran, it had to face a global technology denial regime for nearly four decades. Did India collapse? The answer is an emphatic **No.** The technology denial only compelled Indian scientists and engineers to try to develop technology alternatives locally. This augmented Indian self-reliance in nuclear technologies alongside a host of new and strategic areas.

In space technology, Indian achievements are multidimensional, comprising launch vehicles, communication satellites, navigational satellites, and remote sensing satellites. India successfully launched the Chandrayan-I mission to the Moon and the Mars Orbiter Mission (Mangalyan) to Mars, and is well on the way to launching Gaganyan, to put Indian astronauts in space. A confident India has now started the commercial launch of satellites for other nations at very competitive costs.

With the liberalisation of the Indian economy in 1991, much against the general perception that Indian industries will collapse under global competition, several Indian industries have become more competitive in the international marketplace.

The automobile industry in India- which had been traditionally based on licensed manufacture, presently designs, and manufactures two-wheelers, three-wheelers, passenger cars, commercial vehicles, and more recently electric vehicles- employs about 30 million persons directly or indirectly, and contributes more than 7% to the overall GDP.

India also utilised the opportunity to become a massive hub for Business Process Outsourcing and develop a formidable IT industry with footprints across the world. It employs over 5 million people in high-paying jobs.

At the time of independence, the total installed capacity of electricity production in the entire country was about 1.4 GW out of which 63% was generated using coal and the rest was from hydroelectricity. Most of rural India was out of this electricity network. The installed capacity now stands at about 400 GW, with fossil fuels contributing to 58% of the electricity production, while the rest comes from green sources, such as solar, wind, hydroelectricity, and nuclear energy. Now all the villages of India are electrified. India is one of the countries in the world with a national grid and is leading the International Solar Alliance.

Transport infrastructure is yet another area where India has made rapid and visible strides in recent years. Starting from about 20 thousand kilometres of National Highways and 400 thousand kilometres of road networks in India in 1947, India today has emerged as having the second largest road network in the world with a modern multi-lane National Highway network of 150 thousand kilometres and a roadway network of 6.2 million kilometres. The economic impact of this, including on employment generation cannot be ignored.

India also had a colonial railway network of about 54000 km fragmented into broad gauge, metre gauge and narrow gauge- mostly single track, powered by coal. It has now increased to about 126000 km; mostly electrified and generally with multiple tracks. Considerable technology upgradation of the rolling stock has also taken place during recent years.

India's resilience to natural calamities like droughts, floods, cyclones, earthquakes, and tsunamis has additionally increased substantially over the decades, both because of pre-disaster warning capabilities and post-disaster rescue and relief capabilities.

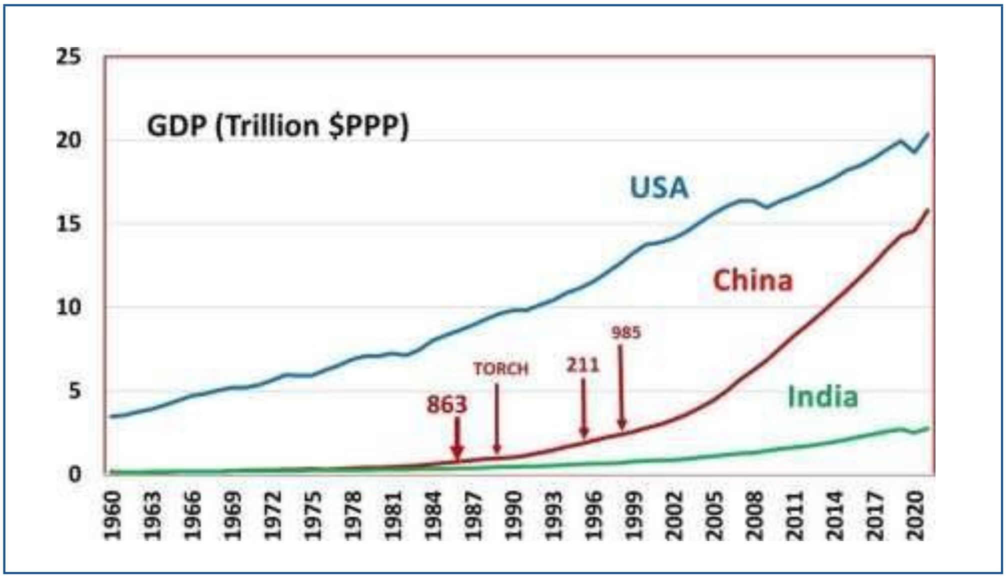
Even though several other success stories deserve to be on this list, we have stated above only some illustrative examples that demonstrate that India is also growing on the strength of its indigenous resources and Science and Technology strengths.

There has been undeniable economic growth during these decades. However, India's share of international trade has remained low and with a GDP of about 3 trillion USD in 2021, India continues to remain in the comity of developing nations, with an aspiration to become a developed nation in the next few decades. Some readers may recall that Hon'ble Prime Minister, Shri Narendra Modi, while addressing the audience at the Global Investors Meet in Bengaluru (November 2, 2022), announced that India is setting a target of 2047 to become a developed nation. It is certainly a welcome sign of hope for the realisation of a long-cherished dream of our forefathers who struggled to gain freedom from colonial rule and build a sovereign, prosperous state. However, for people in our age group, (VSR was born five years before independence while DKS was born five years after independence) it is hardly solace since we may not be alive to see that day. Is Science and Technology based development not fast enough to lift a developing country into a developed nation within one generation?

II
The China Story: Something to Learn?

One cannot resist the temptation of spending a few minutes looking at one of our neighbours, the People's Republic of China (PRC). The PRC was founded on October 1, 1949, almost at the same time as the Indian Republic. In the early years, the PRC essentially followed the Soviet model of governance. For various reasons including political and social upheavals like the Great Cultural Revolution, the Chinese economy essentially followed a model of governance typical to that of a developing economy for nearly four decades, and remained conspicuously similar in magnitude to India. For example, in 1989, while the US was leading the world with a GDP of $5.642 trillion, China was in the third position with $1.025 trillion GDP, and India was in the fifth position with $0.878 trillion GDP. It is indeed a puzzle that from the beginning of the twenty-first century, China is galloping ahead, both technologically and economically. In the world listing of countries by GDP in 2022, the USA still led the world with $20.89 trillion. China occupied the second position with a GDP of $14.72 trillion while India occupied the sixth position with a GDP of $2.66 trillion. Undoubtedly, as shown in Fig.1, China moved on to a different growth trajectory- the trajectory of developed nations, that too in a short span of ten to twenty years.

Fig. 1: Growth of Gross Domestic Product of the USA, China, and India along with some Critical Interventions [1]

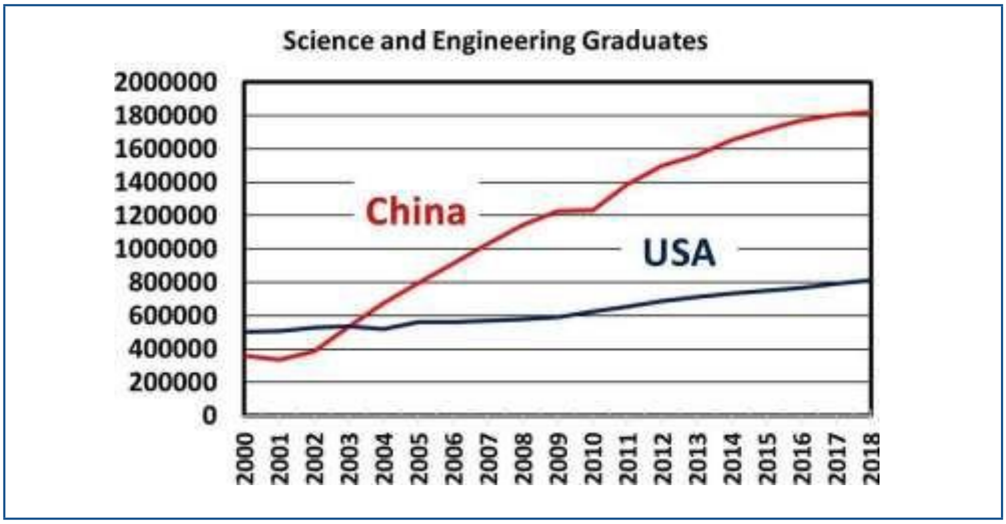


How did this happen?

Looking back, the Chinese growth story can be attributed to four critical interventions implemented by the Chinese Government during the eighties and nineties (see the arrows in Fig. 1). Two early interventions included a 'State High-Tech Development Plan' (Programme 863, 1986) aimed at stimulating research and development not only in the three strategic sectors of nuclear, space, and missile defence but also in various key Science and Technology areas. Another dedicated program- Programme TORCH- was launched in 1988 to create ecosystems and infrastructures necessary to support innovation and entrepreneurship among Science and Technology professionals. While the three strategic sectors experienced significant growth under the new plan, Chinese contributions to the generation of new knowledge through publications in refereed journals, Intellectual Property generation, growth of industries outside the strategic sectors, and their impact on the Chinese economy remained relatively marginal.

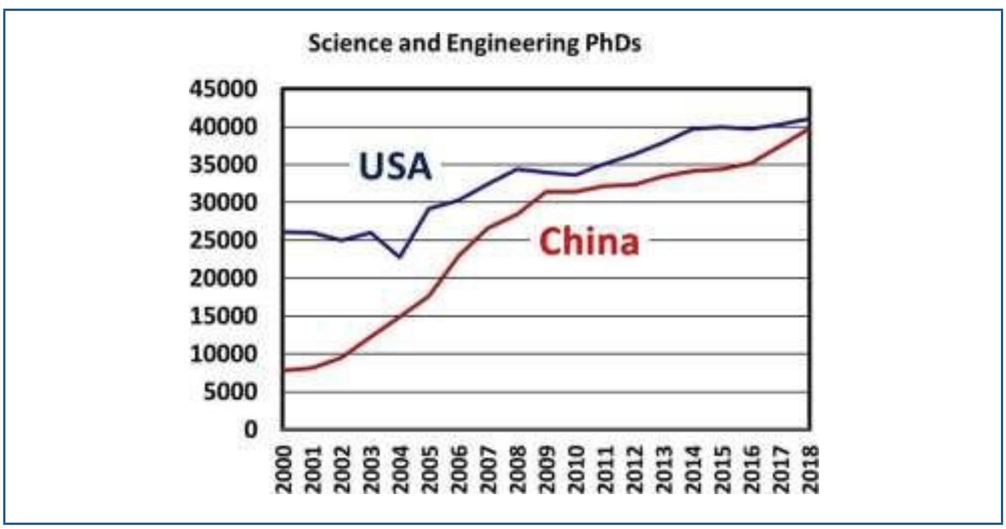
The need to induct more students to take up higher education and research, and to strengthen them to internationally competitive levels was soon realised and led to two new initiatives- **Project 211, 1995** to strengthen education and research in about a hundred institutions of higher learning in critical disciplinary areas, and **Project 985, 1998** to create world-class universities as a national priority for the twenty-first century to "enhance the capacity of high-level manpower in the frontier fields of science and technology".

Fig. 2: Science and Engineering Graduates in China and the USA [1]



Did the interventions work? Figs. 2 and 3 show the growth of first university degree holders and doctoral degree holders in natural sciences and engineering during the early years of the twenty-first century.

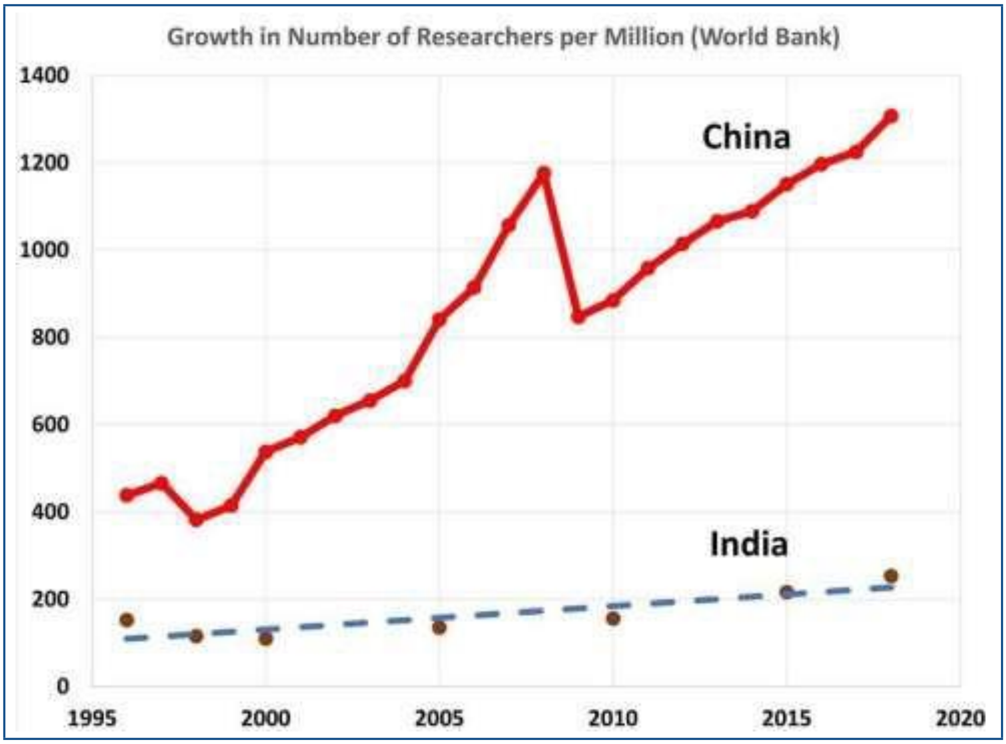
Fig. 3: Science and Engineering PhDs in China and the USA [1]



It is interesting to note that while in the year 2000, Chinese Universities awarded less than half the number of doctorates in STEM as compared to US universities; by 2010, the numbers from China became comparable to the numbers from the US. Based on present enrolments, it is estimated that by 2025, China will have nearly double the number of STEM PhD graduates as compared to the United States.

We show in Fig. 4 the growth of researchers per million population in China according to the World Bank.

Fig. 4: Researchers per Million Population during 1995-2022.



These programmes have already resulted in a pyramid (Fig. 5) of excellence in the Chinese education system [2].

Fig. 5: Pyramid of Chinese Higher Education Institutions (2015; adapted from [2])

Countries like the USA have shown that innovation and entrepreneurship are key to drawing economic benefits out of scientific strengths. Silicon Valley and Boston Route 128 are well-known examples of this. China has also built an innovation and entrepreneurship ecosystem, to convert technical knowledge into wealth. The 1988 TORCH programme was the first initiative taken by China to venture into technology innovations and entrepreneurship. With support from the United Nations Fund for Science and Technology (UN FS&T), China started the Technology Business Incubation (TBI) programme in Wuhan in 1989. Interestingly, five Indian experts from the Entrepreneurship Development Institute, Ahmedabad, employed by UN FS&T, played a major role in preparing the Chinese program of Technology Business Incubators.

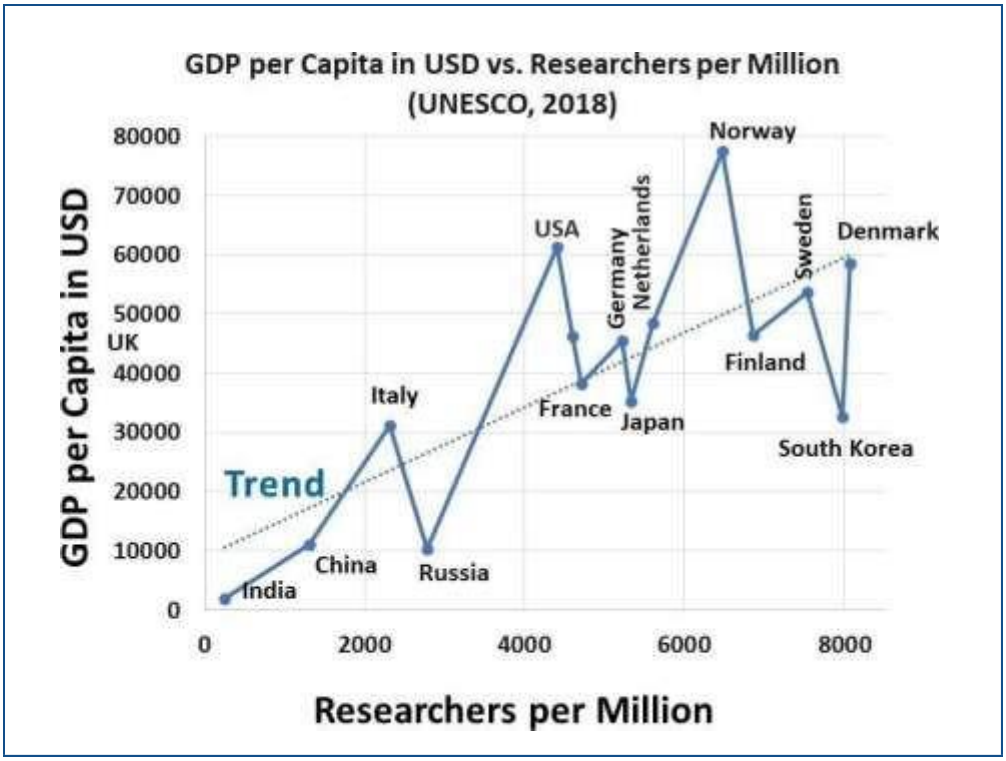
By the year 2000, China had established nearly 200 TBIs. At the end of 2016, China was home to 3255 TBIs with a further ambition to increase the number of incubators including a few incubators overseas (Fig. 6).

Fig. 6: Growth of Technology Business Incubators in China [3]

A survey in 2015 revealed that about 6-8% of the technically trained people in China are reported to be involved in some kind of entrepreneurial activity. This number is also very similar to that of developed countries.

There is also a well-known correlation between the number of researchers per million population in a country and their per capita GDP taken from UNESCO reports, which can be seen in Fig. 7.

Fig. 7: GDP per Capita versus the Number of Researchers per Million population of some selected developed economies



There is no doubt that China is reaping the benefits of increasing the number of R&D personnel as increasing GDP.

Having tasted success, it has already launched the next initiative in the human resource development sector- the World First Class University and First-Class Academic Discipline Construction, together called the ***Double First-Class University Initiative (2018)***. The initiative has the same goal as the earlier Project 211 and Project 985, *viz*., to strengthen Chinese universities and the educational system at international levels.

The message is clear. China, while making major investments in Research and Development has also been taking major steps to develop the required human resource to carry out the R&D. Together with the entrepreneurial environment being built in the country and the market pull sustained by proactive government policies, China has not only pulled out of the developing economy trajectory but is also confident of leading the world in the coming decades.

We believe that the China story holds important lessons for all developing countries, in particular India.

III
Back to the India Story: How can India become a Developed Country?

As mentioned, having chosen Science and Technology for development, India had accorded high priority to education and R&D right from day one post- independence. India presently has more than forty million students across its universities and other higher education institutions. India also has about 0.35 million S&T professionals across its educational and R&D Institutions. The national achievements to which this human resource has contributed have already been cited and clearly indicate the global competitiveness of the Indian educational and R&D systems. India has had a spirit of entrepreneurship for a long time (the well-known 'JUGAAD' culture). The country also launched an entrepreneurship development programme and a Technology Business Incubator programme for the new generation of entrepreneurs early. Despite all this, why does India continue to be a developing economy even after seventy-five years of independence?

Let us first look at the quality of education and research in India in an international context. We show in Fig. 8 the number of R&D publications in refereed journals for the top 20 countries during 1996-2021. We see that India needs to catch up not only with some of the scientifically advanced countries like the US but also with China. Does this imply that the creativity of researchers in India is poorer than those in developed countries? We show in Fig. 9 a comparison of the number of research publications per year per researcher in S&T in 2020. We can deduce that the creativity of researchers from India is comparable to and even better than those from most advanced countries, including China.

Fig. 8: R&D Publications by Top 20 Countries During 1996-2021 [4]

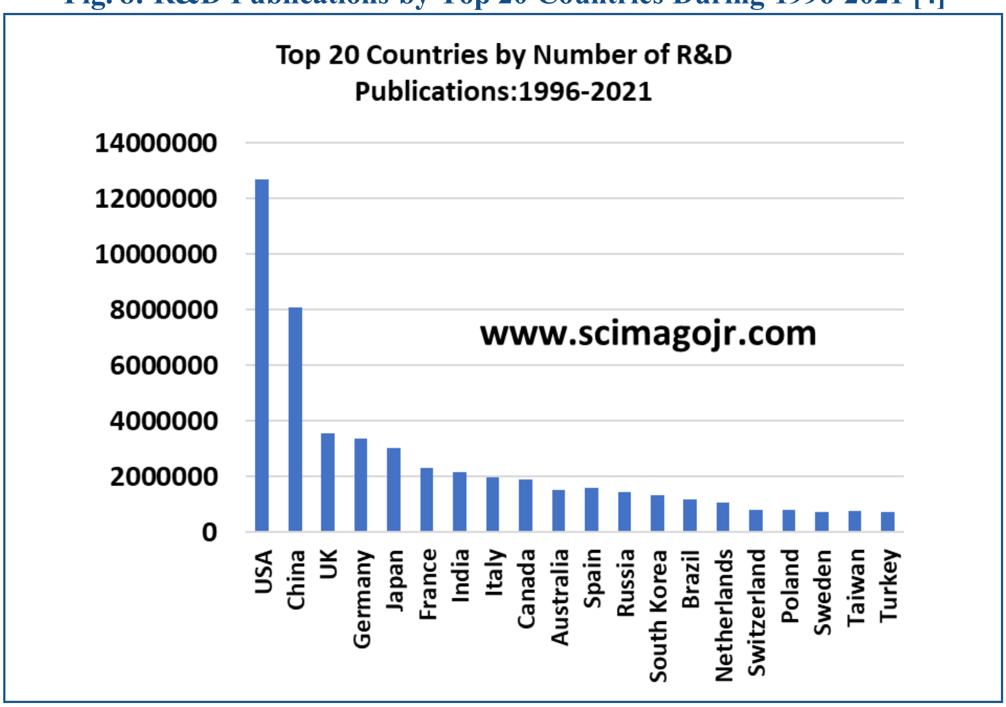
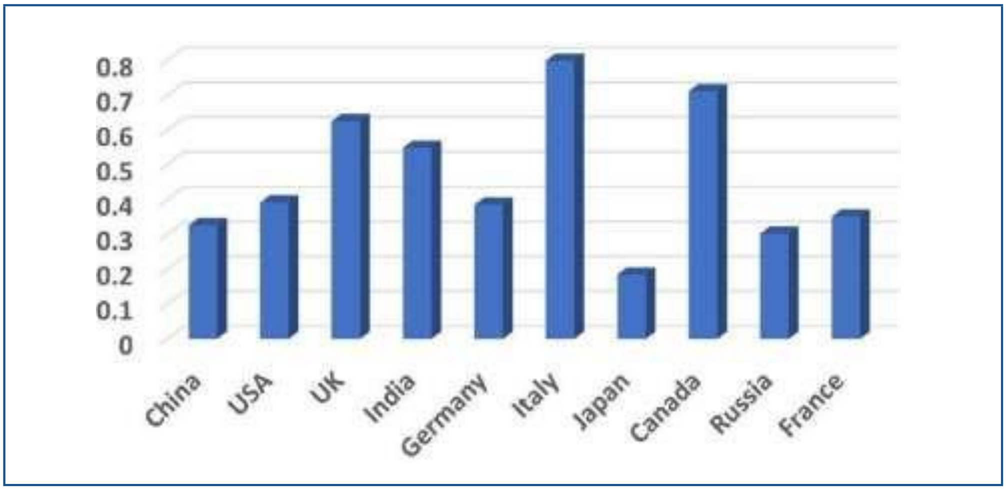
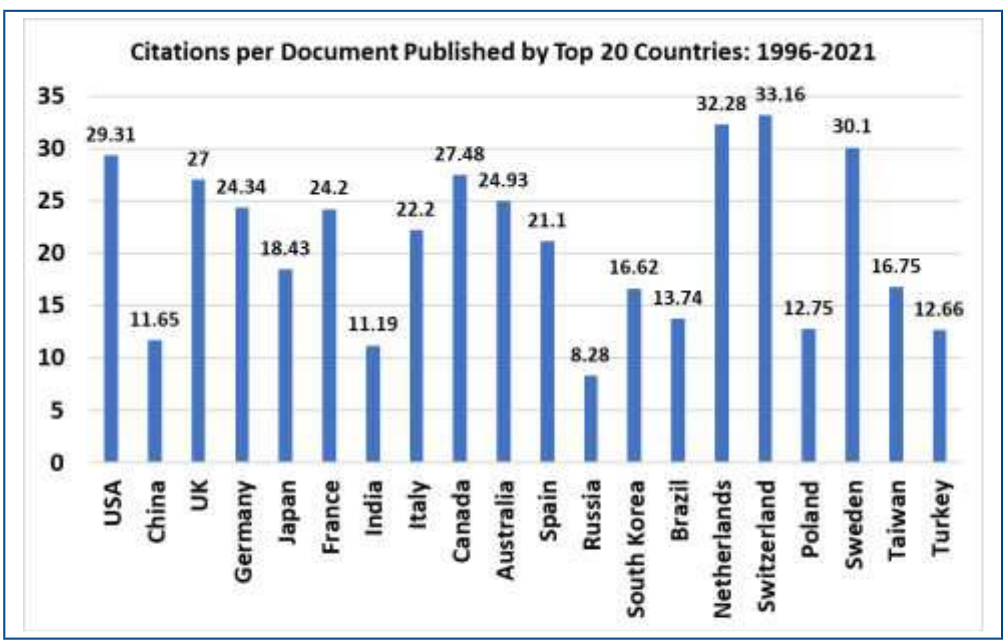


Fig. 9: Number of Publications per Researcher during the Year 2020 in S&T according to SCOPUS.



Another indicator of the quality of research is the average number of citations a research paper gathers over time. Fig. 10 shows the citations per document published by scientists from different countries from 1996 to 2021, as shown earlier in Fig. 8. It is satisfying to see that in terms of the number of citations per document, India, while lagging behind scientists from the developed part of the world, compares favourably with China, implying that the quality of publications of Indian researchers is very similar to those of Chinese researchers. The real problem with India is indeed the small number of researchers in the country as shown in Fig. 11 (see later).

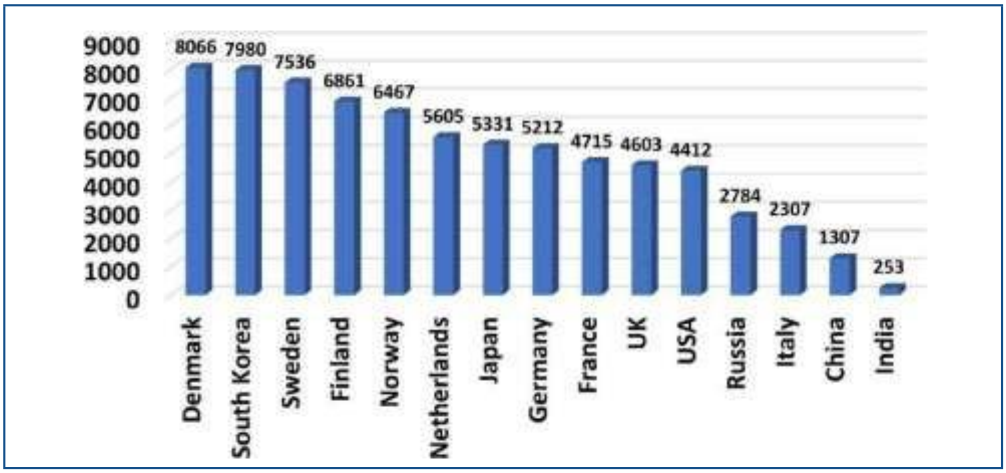
Fig. 10: Citations per Publication for Countries [4]



The above analysis should dispel any doubt about the productivity and quality of Indian scientists, despite the well-known issues of inadequate funding and facilities.

Fig. 11 shows the number of researchers per million population in India and in some selected developed countries, taken from UNESCO reports. We immediately note that the number of researchers in India is far below the norm in most developed countries and China.

Fig. 11: Number of Researchers per Million Population in Some Selected Countries in 2018 (UNESCO)



We believe that the low percentage of researchers in Indian universities, typically about 10%, compared to about 30% in most leading universities in developed countries (and China), is primarily responsible for this. To bring out the crucial role of researchers in S&T in the economic growth of the country, we show in Fig. 12 the GDP per Capita of India and China during 1990-2022.

Fig. 12: Growth in GDP per Capita of India and China during 1990-2022.

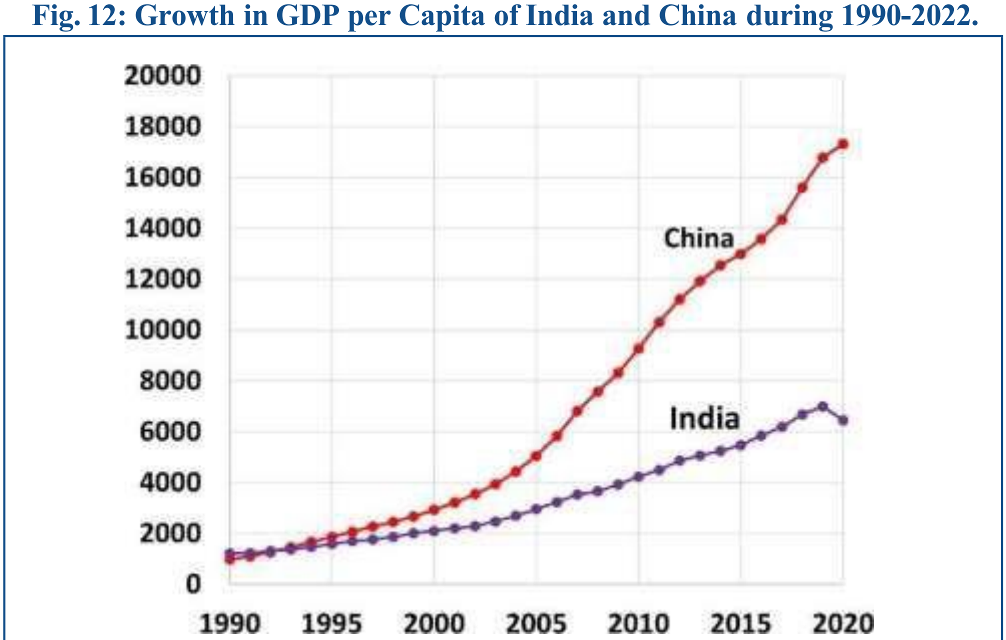
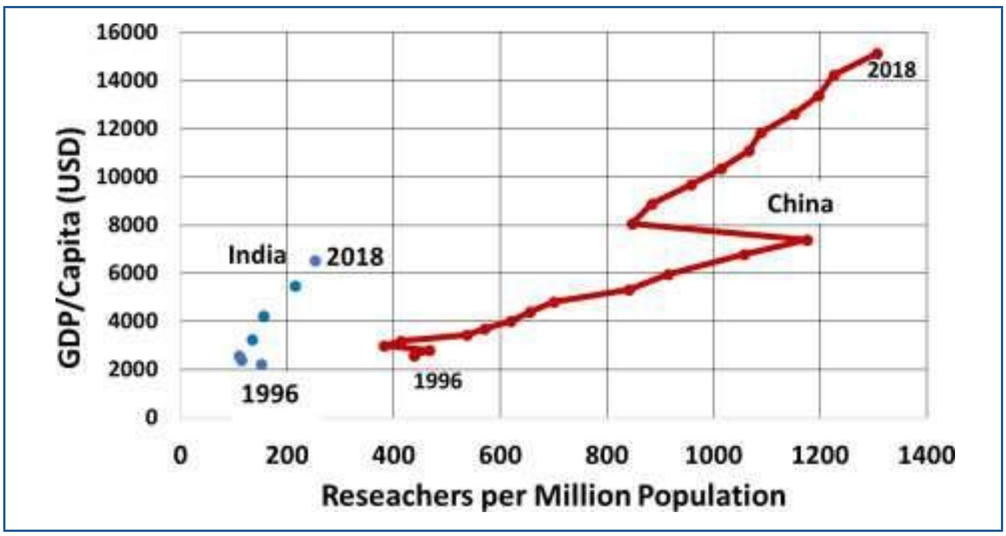


Fig. 13 shows the GDP per Capita versus the number of researchers per million (taken from Figs. 4 and 12) for China and India. But for local ephemeral deviations (perhaps due to the vagaries of classification of data over sharp divisions of time) the trend is very clear- the GDP per capita of China essentially rose monotonically with an increasing number of researchers per million population. On the other hand, India, while missing the per capita GDP growth driven by the number of researchers per million population, seems to be benefiting mostly from better investment strategies. Clearly, the Chinese strategies have yielded faster and better results.

Fig. 13: GDP per Capita vs. Number of Researchers per Million Population of China and India, over the Years.



How did India lose out despite an early start in Human Resource Development?

Let us recall that India was an early starter in higher education. Starting with just four Central Universities (which are in general better funded and arguably better run) in the 1960s, this number has grown to more than fifty by now. The setting up of the first five Indian Institutes of Technology in the early years after Independence was a major step in engineering education in the country. This was followed by the setting up of two Institutes of Management in 1961 in an attempt to provide essential skills in managing businesses and industries. However, as shown in Figs. 14-16, India did not maintain the early momentum in the growth of the number of these institutions. One cannot miss the repeated breaks in time seen in setting up these centers of quality education. The stagnation in the number of institutions of higher learning is highly frustrating to generations of students who were aspiring for quality education.

Fig. 14: Growth of the Number of Central Universities in India

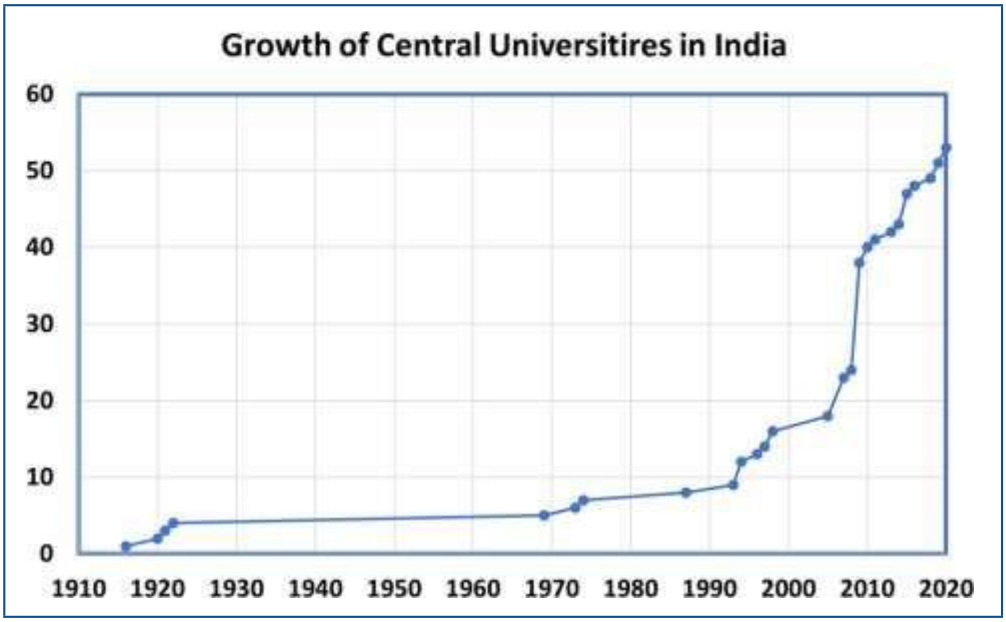


Fig. 15: Growth of the Number of Indian Institutes of Technology

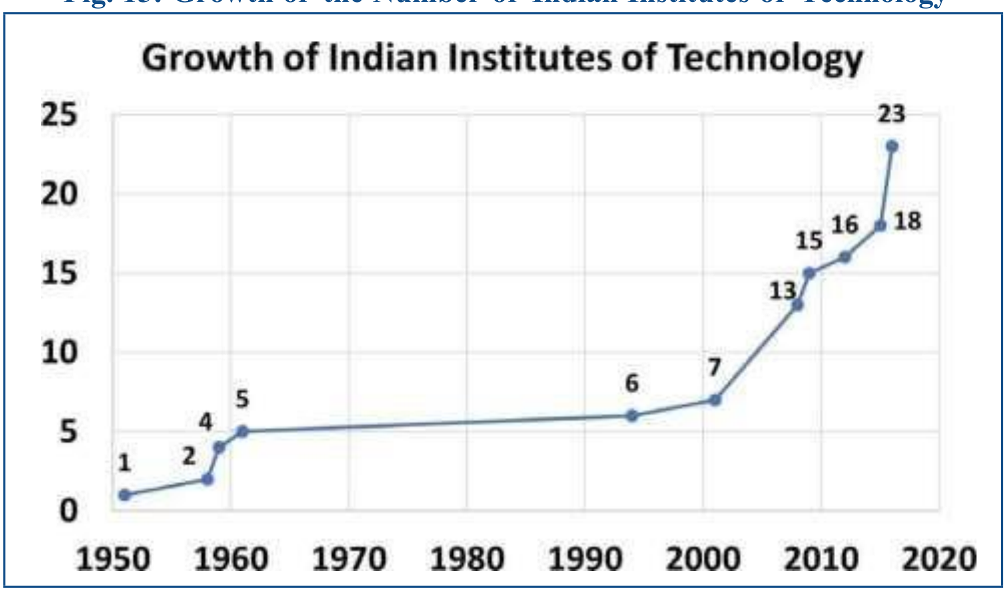


Fig. 16: Growth of the Number of Indian Institutes of Management

The story is not different in medical education. The All India Institute of Medical Sciences was founded in 1956. The second AIIMS came into existence in 2012. At present, there are 23 AIIMS campuses out of which 20 are functional. It is not surprising that a multitude of Indian students must depend on institutions with large capitation fees or proceed to other countries for getting a medical degree. Even China has started offering medical education to Indian students.

One can easily imagine how India has deprived and starved itself of trained human resources for decades by not providing its youth access to higher education and training in modern engineering and technology, management, and health care, which could have done wonders for the economic development of the country. It is however very heartening to note that India is now taking appropriate and corrective steps to strengthen higher education to suit the coming decades.

A fraction of the technically trained people also have a flair for entrepreneurship. Every entrepreneur is not only a wealth generator but also an employment generator. India has always been known for the entrepreneurial spirit of its population (the so-called "JUGAAD" culture [5]). Nevertheless, venturing into entrepreneurship based on emerging technologies is a new cup of tea for India.

According to a recent report, (Global Entrepreneurship Monitor 2020), the percentage of technically trained people engaged in entrepreneurship in India and China is almost the same (3.1%). With a much smaller number of technically trained people, it is not surprising that India also has a much smaller number of technopreneurs.

The setting up of the National Science and Technology Entrepreneurship Board (NSTEDB) in 1982 marks the beginning of technology-driven entrepreneurship in India. With support from the United Nations Fund for Science and Technology (UN FS&T), India started the Technology Business Incubation (TBI) programme in 1989 along with China. Unfortunately, the growth of the entrepreneurship development programme in

India was much slower than in China. Fig. 17 shows the growth of TBIs in India according to the Ministry of Electronics and Information Technology and the National Association of Software and Service Companies. It is vividly clear that India is falling behind China in exploiting Technology Business Incubation.

Fig. 17: Growth of Technology Business Incubators in India

India has seen several young entrepreneurs in the last two decades who have made it proud in diverse areas of technology. An aggressive program in entrepreneurship development and technology business incubation can clearly nurture an increasing number of technopreneurs who in turn can generate more wealth and employment simultaneously

In summary, for nearly five decades after they emerged as newly independent nations, both the Indian and the Chinese economies remained neck to neck and comparable to typical developing economies. However, China has been charting a new path of rapid economic growth since the beginning of the twenty-first century, and we argue that this has been made possible by the strengthening of its educational and entrepreneurial infrastructure. It is crucial for India to address not only its educational pipeline and boost the number of S&T personnel to levels comparable to China and other developed countries but also to foster and enhance the environment for innovation and entrepreneurship in all technology domains, including emerging ones. It should also be realised that a manufacturing economy reaches its fullest potential only when it is innovation-driven.

China has also benefited from the bootstrap effect of increasing GDP on education and research investments. Presently, with a GDP of nearly 18 trillion USD, China spends 3.5% of its GDP on education and research, while India, with a similar population but a GDP of only 3.3 trillion USD, allocates 2.9% of its GDP to the same. In absolute terms, this translates to seven times larger investments in R&D by China compared to India. As a result, China can support a larger number of researchers.

In Summary

What does India need to do to attain its rightful place amongst the comity of nations of the world and attain it fast?

1. India needs to fix its educational pipeline and bring more students into higher education and research so that the number of R&D personnel per million population in India grows to levels comparable to developed countries.

   The faculty strength even in our premier universities hover around 500-1000, and have been stagnant at this level for several years. Universities in most developed countries and China have much larger faculty and student strengths.

2. India needs to further strengthen its ecosystem for Innovation and Entrepreneurship so that its S&T strengths turn into its economic ones. Entrepreneurship training and business incubation should be made an integral part of education.

3. Industries may be encouraged to participate in and nurture entrepreneurship training and business incubation.

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