To become a knowledge economy*

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To become a knowledge economy, we must seek excellence in basic research (including directed basic research) and applied research. We need enhanced academia–industry interactions and also excellence in R&D-led innovation. All this must be backed by high-quality manufacturing skills. We need an excellent research and innovation ecosystem, whose components are talented young people, high-quality faculty in the education system, adequate funds, strong infrastructure including an e-science infrastructure, appetite for risk-taking, ability to leverage international cooperation to strengthen indigenous initiatives and scientific leaders. We must also remember that 'national development and national security are two sides of the same coin'. The metrics for evaluating the progress of science and technology in the country must also include the achievements of the mission-oriented agencies and the successes in rural technology delivery. India must be prepared to be the first introducer of new advanced technologies. The so-called proven technologies, unless subjected to continuous evolutionary improvements, are often a synonym for obsolete technologies.

Keywords: Academia–industry interactions, innovation, knowledge economy, rural development.

SCIENCE and technology-driven growth is needed to become a 'developed' country. But for this development to be sustainable, a knowledge-driven economy is essential. This requires global leadership in science, engineering, technology, manufacturing and innovation. Excellence is needed in basic research (including what I have called 'directed basic research')[1] and in applied research (including 'pre-competitive applied research') through enhanced academia–industry interactions, particularly in 'critical technologies', as determined by technology foresight analysis. We also need excellence in R&D-led technology development and innovation. All this must be backed by high-quality manufacturing skills. Our vast S&T system and the university system have created the base today for converting the Indian economy into a possible knowledge-driven economy.

The Office of the Principal Scientific Adviser to the Government of India (PSA) and the Scientific Advisory Committee to the Cabinet (SAC-C) have a multi-departmental role. The scientific business of the government has been divided into many scientific departments. But there are subjects which fall in nobody's territory. And there are subjects, bits and pieces of which fall in many territories. These are the areas PSA's Office and SAC-C focus on. The PSA is also ex-officio Chairman of the SAC-C. The SAC-C has, as members, all the secretaries of the scientific departments, presidents of the science/engineering/agricultural academies, presidents of industry associations – CII, FICCI and ASSOCHAM, and some other leading scientists and intellectuals.

PSA's office has held brain-storming sessions and has prepared reports (under the guidance of SAC-C) on a wide range of subjects – from nanoelectronics and Indian Research and Education Network (REN) to photonics and quantum matter physics to additive manufacturing (an integral part of the Third Industrial Revolution, driven by the Internet) – to provide roadmaps for these areas. PSA's Office is funded by the Government for 'synergy projects'. The initiative on nanoelectronics led to the establishment of Centres of Excellence in Nanoelectronics in IISc, Bangalore and IIT Bombay and the initiative on REN (taken in collaboration with the National Knowledge Commission) led to the creation of the National Knowledge Network. Some other examples are the establishment of Core Advisory Groups for 'pre-competitive applied research' in various technology sectors (automotive, machine tools and electronics hardware) and the Rural Technology Action Group (RuTAG), which is an open platform innovation strategy for rural technology delivery.

Measures of progress in science and technology[2]

The metrics for basic research are the number of publications and their impact factors; the originality of the problems and their importance to science are also relevant. The metrics for industry-oriented applied research and technology development are patents and R&D-inspired innovations. The metrics for the application of science and technology for rural development (needed for inclusive growth) can only be related to success in rural technology delivery. The achievements of the mission-oriented agencies like the successful Pokhran tests, the perfect

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launching of missiles and satellites, indigenization of the design and construction of nuclear power reactors, etc. though they do create a sense of great pride in the country, are difficult to be represented by metrics like papers or patents. For a large country like India innovation also has many dimensions[3] and each dimension should have its own metric. All these aspects of science and technology are relevant as India puts in efforts to become a developed country and then a knowledge economy.

The results from basic research, when published, become global property. And the country or countries which have the needed industrial infrastructure and manufacturing skills, will use the knowledge generated from such basic research, wherever possible, into wealth-creating products and processes. As William Press[4] says, '… information flows today are so rapid that anyone, anywhere, can potentially be the entrepreneur who recognizes the economic potential of scientific discoveries …'. He calls it the 'appropriability conundrum'! The country where knowledge originated through basic research, particularly if it is a developing country, may not benefit in those areas where there is no backup from applied research, technology development and manufacturing skills. Nuclear science and technology, space science and technology, and knowledge chemicals are examples of scientific areas in India, which are exceptions to the above handicap, and as the country moves towards the goal of becoming a knowledge economy, more and more such areas, I am sure, will emerge rapidly.

The components of an excellent research and innovation ecosystem

The components of an excellent research and innovation ecosystem are talented young people (and then there are also the young gifted, to identify and nurture whom there is a pilot project initiated from the PSA's Office); high-quality faculty in the education system (including in schools); adequate funds; strong infrastructure, including an e-science infrastructure; appetite for risk-taking; international collaboration (to leverage this collaboration to strengthen indigenous initiatives) and scientific leaders. The three great scientific leaders – C. V. Raman, the greatest experimental physicist India has produced; H. J. Bhabha, the founder of our atomic energy programme, and Srinivasa Ramanujan, whose genius has been compared by Hardy and Littlewood to those of Euler, Gauss and Jacobi – were very different in the nature of their scientific work, but they always focused on important and original problems. Raman and Bhabha created their own ecosystems. Ramanujan was a soloist and did not need an ecosystem!

National development and national security

Fourteen years back (in the Tenth Nayudamma Lecture, November 1999), I said that 'National development and national security are two sides of the same coin'. I had said in a meeting of the Indian National Academy of Engineering in 2009 (ref. 5) that 'Development without Security is vulnerable; Security without Development is meaningless. In the context of nuclear deterrence, we must remember that the greatest advantage of recognized strength is that you don't have to use it. And that the greatest disadvantage of perceived weakness is that your enemy may get adventurist'. I had also said there that 'The design of nuclear weapons, … with exactly predictable yields, requires expertise in many areas of physics: explosive ballistics, shock wave physics, neutron kinetics, and physics related to radiation coupling of the two stages in the case of the thermonuclear device. Precise estimation of design yields also requires complex computer calculations … accurate determination of the yields after the tests requires capabilities in advanced seismology and radiochemistry.'

The Pokhran May 1998 nuclear tests were the culmination of a committed team effort. As I have said[6]: 'It is universally recognized that India's nuclear weapon development programme is based on self-reliance[7] … when we refined our computer calculations for the designs we tested, physics knowledge had advanced tremendously in every field (compared to the Manhattan days) … (also) the number of (USA) tests per year came down with increase in available computing power … the May 1998 (Indian) tests were fully successful in terms of achieving their scientific objectives … establishing the computer simulation capability to predict the yields of nuclear weapons – fission, boosted fission, and two-stage thermonuclear – of designs related to the designs of the devices tested by us … Thus the carefully-planned series of tests carried out by us gave us the capability to design confidently and build nuclear weapons from low yields up to around 200 kilotons. A great deal of further scientific and technical development work has taken place since then'.

'Small science' and 'big science'

Raman discovered the Raman effect with the help of a few students. Much of research is done today also in this fashion. But very often these scientists use large facilities like synchrotron radiation sources, particle accelerators, research reactors, etc. which require large, multi-disciplinary engineering teams to build. Personally I do not, therefore, see a clear distinction between 'small science' and 'big science', because they are so intimately connected. And then there are unique multi-billion dollar facilities like the Large Hadron Collider in Geneva (CERN), built through international cooperation, to answer specific and important questions like the existence of the Higgs boson, predicted by the Standard Model of particle physics, and to simulate the early stages of the 'big bang'. India contributed 40 million US dollars worth of equipment (leader: RRCAT, Indore) –

superconducting sextupole, octupole and decapole magnets and advanced grid software – to this facility. India is also contributing to and participating in experiments with two detectors – CMS (leader: TIFR, Mumbai) and ALICE (leader: VECC, Kolkata) – and analysis of data from them. The first signatures of the Higgs boson came from the CMS detector, and this major scientific event has been recognized by the award of the Nobel Prize in physics to Higgs and Ecklert, who predicted the existence of the Higgs field.

The Indian space and nuclear programmes

We have had a very successful space programme and the satellites launched by ISRO have changed our lives through providing transponders for communication and by providing important information about our natural resources and weather conditions, including information that enables the country to respond better to natural disasters. The Polar Launch Vehicle (PSLV) of ISRO is a robust vehicle and has launched most of our satellites, as well as a large number commercially for other countries. It also launched the Mars Orbiter, which is now on its long journey to Mars. In the first week of December, ISRO also had its first successful launch of its Geostationary Launch Vehicle (GSLV), with an indigenous cryogenic engine.

Our nuclear programme is wide-ranging, though seen generally in the context of nuclear power and national security. The fallouts from our nuclear programme have also, however, been in the areas of particle accelerators and lasers, research reactors and synchrotron radiation sources (for providing neutron, X-ray and optical beams for research in physics, materials science, chemistry and biology), nuclear medicine and nuclear agriculture, water management, etc. and for industry applications.

The enormous scientific and technological success of our space programme and our nuclear programme, and their impact on our development, cannot be measured by the number of papers published in these areas and their impact factors! The metrics for measuring this success are qualitative at present, but must be kept in mind when we speak about India's ranking in science and technology in the global arena.

The importance of nuclear energy

In a lecture in BARC in March 2013, Yukiya Amano, Director General, IAEA said that 'there are 66 (now 73: R.C.) new reactors under construction. Seven of them are in India. Other major users of nuclear power such as China and Russia also have significant expansion plans. A number of countries have taken the decision to introduce nuclear power, including Egypt, Jordan, Nigeria, Poland, Turkey and Vietnam. The United Arab Emirates has started building a nuclear power plant, the first *new* country to do so for 27 years. He also said that 'India is at the forefront of technological development in the nuclear sector, not least in the area of fast reactors and related fuel cycles. Fast reactors and related fuel cycles will be important for the long-term sustainability of nuclear power.'

Fast breeder reactors are an important part – the second stage – of our three-stage nuclear power programme. India now has a nuclear installed capacity of 5780 MWe, including the first Kudankulam VVER-1000 reactor, which attained criticality on 13 July 2013. The operating reactors in India have an excellent performance profile – high availability factors (above 90%), high plant load factors (above 80%) and, in the last few years, as many as 10 reactors have recorded continuous run of more than one year (370–529 days). We have a track record of over 380 reactor-years of safe operation, and no incidence of radioactivity release beyond the stipulated limit of the regulatory body, AERB. The excellence of our safety culture in the nuclear field has been internationally recognized.

As regards our future plans, we have one reactor under commissioning, the second VVER-1000 Light Water Reactor at Kudankulam, and five reactors under construction: the 500 MWe Prototype Fast Breeder Ractor (PFBR) at Kalpakkam and four 700 MWe Pressurized Heavy Water Reactors (PHWRs), two each at Kakrapar and Rawatbhata. These will raise the installed nuclear capacity to 10,080 MWe by 2017; this the Department of Atomic Energy (DAE) hopes to raise to 27,480 MWe by 2023–24 and to 63,000 MWe by 2032. Beyond that, further expansion is planned by DAE using Fast Breeder Reactors and later the thorium-based reactors.

The reactor in the Indian nuclear submarine ARIHANT, which went critical on 10 August 2013, is a Pressurized (Light) Water Reactor (PWR). Earlier the land-based prototype reactor, became operational in September 2006 at Kalpakkam. Based on the experience of design, analysis, fabrication, commissioning and operation of the PWR for the propulsion programme, India has taken up design of an indigenous PWR, whose construction is expected to be started within five years (S. Basu, private commun.).

Nuclear is now an accepted mitigation technology in the context of the climate change threat. But if it is to be a sustainable technology, the nuclear fuel cycle has to be closed[8], as planned in India's three-stage nuclear power programme. In the report[9] prepared at the request of the Director General, IAEA, an independent Commission (I was a member) mentioned that 'Expanded use of nuclear technologies offers immense potential to meet important development needs. In fact, to satisfy energy demands and to mitigate the threat of climate change – two of the 21st century's greatest challenges – there are major opportunities for expansion of nuclear energy in those countries that choose to have it'. Lessons have been learnt from the 2011 Fukushima accident in Japan by all nuclear countries, particularly on the continued functioning of post-shutdown cooling systems after extreme natural events. But the above conclusion on the importance of the nuclear option, in my opinion, remains unchanged.

I have been saying for two decades and more (see, for example, ref. 10) that the two measures of development for a country like India are per capita electricity consumption and female literacy. India cannot become a developed country, and certainly not a knowledge-driven economy, unless it becomes near-hundred per cent literate without gender discrimination. But that is not enough. Energy is the driver for development. The per capita electricity consumption in India should also go up by six to eight times. That is why all energy options, including nuclear, are so important for India.

Advanced ultra super-critical thermal plant – an example of synergizing exceptional component capabilities

In the context of the climate change threat, it is important to develop energy technologies like nuclear, hydro (both large and mini-hydel plants) and renewable (solar, wind), which do not emit carbon dioxide, the major greenhouse gas, during energy production. But it is a fact that, at least for the next two decades, most of our additional electricity production will come from burning coal. So we are trying to develop the coal-based Advanced Ultra-Supercritical Thermal Plant (AUSTP), which nobody has built in the world so far.

This is not a zero carbon-emission but a relatively cleaner coal-based technology. In the Advanced Ultra Super-critical (USC) coal-based plants, the steam temperature is 700–750°C. A Consortium of Indira Gandhi Centre for Atomic Research (IGCAR), Bharat Heavy Electricals Ltd (BHEL) and National Thermal Power Corporation (NTPC) has been formed, to synergize exceptional component capabilities, through PSA's Office for developing this technology. Two new indigenous materials have been developed by IGCAR for boiler tubes: 304HCu SS tubes and alloy 617 M tubes. They have been produced by Mishra Dhatu Nigam Ltd (MIDHANI) and the tubes have been drawn by the Nuclear Fuel Complex. A test loop will now be set up by BHEL/NTPC.

Industrial development vs rural development

For industrial development, enhanced academia–industry interactions are needed because, in the chain research–development–delivery, while academic institutions are good in research and industry is good in delivery, both are weak in the development segment. On the other hand, in the case of rural development technology delivery is the problem. We initiated, therefore, through PSA's Office, the Rural Technology Action Group (RuTAG)[11], which is an open-platform innovation strategy. We work with voluntary organizations led by scientists or which have a strong scientific component; after a technology has been delivered, the scaling up of the innovation is done through state support. Rural technology delivery has to be based on *Gandhian* economics, which demands that technological interventions should lead to wealth flowing *into* villages, not *out* of villages. RuTAG Centres are currently located in eight IITs and have succeeded in introducing many innovative rural technologies across the country, for example, gravity-based ropeway (IIT Roorkee), improved pirn winding machine and modernized coir ratt (IIT Madras), improved Ambar Charkha and improved puffed rice-making machine (IIT Kharagpur), etc. Under RuTAG, we also work with other academic institutions and national laboratories. Below is an example where the Bhabha Atomic Research Centre (BARC), Mumbai and the Himalayan Environmental Studies and Conservation Organization (HESCO) based in Dehradun were involved[12]. In the hilly areas of Uttarakhand, during the rainy season water runs away downhill and *khaals* (or water reservoirs) are built on the hilltops for rainwater harvesting, which then recharge the acquifers. Here springs are the only available source of water for domestic and agricultural use. As a model project, scientists from BARC used the isotope hydrology techniques (measurement of environmentally stable isotopic ratios of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ and of environmentally radioactive tritium in water samples collected at various heights) and established the water connectivity. Based on the above analysis, subsurface dykes were built at selected locations. Due to this intervention, remarkable success was achieved by rejuvenating the dying springs; discharges have gone up by 2–3 times and new springs have emerged. Almost all the springs are perennial. The locals in this area (Gaucher), I am told, call it *BARC water*! So successful has been this project that it is being replicated at ten places in Uttarakhand and Himachal Pradesh by the State Governments. To help with the water sample analysis, BARC has set up an Environment Lab in the premises of HESCO in Dehradun.

To upgrade the technologies of what I call 'technologically homogeneous MSME clusters', we must provide research, development and innovation (RDI) support through proximate academic institutions, as is being done over the last few years in a programme of TIFAC (DST).

The need for re-innovation (in rural development)

The term 're-innovation' has been used in the context of industrial development by Rothwell and Gardiner[13], and often by China. Rothwell coined the word 're-innovation' to denote successive incremental modifications to a 'generic product' to 'take advantage of emerging technological or market opportunities'. China has often referred to a process: 'introduction, absorption, digestion and re-innovation'.

I use the term 're-innovation', in the context of rural development, in the sense of repetitive, but *suo moto*, innovation, starting from the same core concept and ending in nearly the same product. This kind of innovation seems to be inevitable in the context of rural development because of variations in raw material resource, taste, skills or even culture. Whether it is reactors or rural products, evolutionary changes of existing products are more acceptable than revolutionary designs, however advanced.

Centres of excellence in Frontier areas of science

Research in India is generally funded to support scientists who come out with good project proposals and, when new institutions like the IISER, NISER and the CBS are setup, they also get high level of funding. There are also mechanisms like seed funding for new faculty, special fellowships for outstanding researchers, etc. But it is becoming increasingly clear that, when there is a critical mass of scientists in any institution in any frontier area of science or in an advanced technology area, they should be brought together under a Centre of Excellence. For example, the two Centres of Excellence in Nanoelectronics established in IISc, Bangalore and IIT Bombay, with an MoU between them and an initial support of Rs 100 crores (which has tripled now with funds coming from other sources also); they were established after brainstorming sessions in PSA's Office in 2006 and were funded by DeITY. There is a national Nanoelectronics Users' programme, allowing access to users from other academic institutions; incidentally this has led to 237 projects from 140 user institutions, with 193 papers and 11 patents coming out of the programme (as on January 2014). There is also good international cooperation, but the most important thing is that, in each of the above two centres, 35–40 faculty members from 8 to 10 departments are actively involved and they have attracted a large number of young faculty from abroad. Indian industrial partners are also coming up rapidly.

University research parks

A university research park is a 'cluster of technology-based organizations that are located on or near a university campus in order to benefit from the university's knowledge base and ongoing research'. Effective parks can aid in the transfer of technology and business skills between university and industry teams, encourage the creation of start-ups, and promote technology-led economic development. India's first and only university-based research park is in IIT Madras (M. S. Ananth, private commun., IITMRP).

Some precursor examples include:

- Society for Innovation and Development in IISc, Bangalore.
- Society for Innovation and Entrepreneurship in IIT, Bombay (Mumbai).
- Foundation for Innovation and Technology Transfer in IIT, Delhi.
- Innovation and Incubation Centre in IIT, Kanpur.
- Industrial Consultancy and Sponsored Research Centre in IIT, Madras (Chennai).

I understand from Ananth (former Director, IIT Madras), that IITMRP has filed more than 70 patents in its first one and a half years of existence.

The National Knowledge Network

Electronic connectivity is an important aspect of research collaboration, both national and international. It can also be used for webcasting courses and to access remote advanced research facilities. The National Knowledge Network (NKN) is a multi-10s of gigabit per second core, scaleable, low-latency optical fibre network, with gigabits per second connectivity to about 1500 knowledge institutions (universities and national laboratories) in the country. This project is being implemented by the National Informatics Centre (I chair the High-Level Committee for the NKN) and has made excellent progress; more than 1150 edge institutions are already connected. e-classrooms were our first focus in 2009. When the new IITs were started, they did not have adequate faculty. Old established IITs were asked to mentor the new IITs; for example, IIT Madras was asked to mentor IIT Hyderabad. But how many times can a professor go from Chennai to Hyderabad to give lectures? NKN was useful in this context; the lectures given in Chennai could be heard by students in Hyderabad and, because of the low latency, they could also interact strongly with the professor. Now, of course, IIT Hyderabad has its own faculty. Such virtual classrooms can also be used to share fragmented faculty in super-specialized areas. Protein crystallographers in India have used NKN to access synchrotron sources abroad. In order to enable users to appreciate the power of the network, we had taken up a few model projects (the Virtual Classroom was the first one), like the Climate Change Grid of the MoES, the Brain Grid to enable the brain research scientists working in areas like Alzheimer's disease and dementia, etc. to share clinical research data. The NKN is already being used extensively in the country.

NPTEL on-line courses

With the availability of high-speed electronic connectivity, web-casting of lectures and courses has become popular. There are also what are called 'massive open on-line courses (MOOCs)', the most prominent among them being edX, operated through Harvard–MIT collaboration, and the US west-coast-based Coursera and Udacity. There is a new initiative from the MHRD, which has had a successful National Programme on Technology-Enhanced Learning (NPTEL), where a large number of courses from professors in IITs and IISc have been put into a database with open access. I understand that, in the very large number of accesses, about half are from abroad.

Now there is a new initiative from NPTEL, in cooperation with NASSCOM and companies such as Cognizant, Infosys and TCS, to conduct MOOCs in the following three computer science areas: (1) programming, (2) algorithms and (3) data structures (Bhaskar Ramamurthi, private commun.). The contribution of NASSCOM and the IT companies is a key differentiator for the proposed MOOCs, which can be a valuable employment creator for graduates. The MOOCs will be followed by an in-person proctored exam. The plan is to launch a pilot of the MOOCs, with a limit of 50,000 students. A full launch is being planned from June 2014. I understand from Bhaskar Ramamurthi (Director, IIT Madras), that the MOOC will target between 100,000 and 500,000 graduates in all areas of S&T over the next few years. MOOCs will need the connectivity provided by NKN.

Global leadership in manufacturing

If we want India to be a global leader in manufacturing in the long term[14], we must be willing, if necessary (particularly in a new strategic technology area), to live with products with somewhat lower specifications (compared to what the current global leaders with long experience in manufacturing in the field can provide) in the short term, as long as the indigenous products meet the critical requirements. Then only we will be able to manufacture tomorrow's products at globally competitive or even higher standards. And we must shed addiction to branded products. This is what is inhibiting, for example, the introduction of indigenous diagnostic and therapeutic medical devices and advanced research instruments.

And then there is the so-called 'Third' Industrial Revolution, which is being driven by the internet and by additive manufacturing (3D printing technology), robotics and other advanced technologies and also by a desire to develop green technologies. Additive manufacturing is not dependent on 'economy of scale' and the products can be customized. We must also close the existent technology gaps (vis-à-vis the 'Second' Industrial Revolution).

Conclusion

The path to a knowledge-driven economy is paved by new advanced technologies. India should be prepared to be the first introducer of new advanced technologies, after, of course, assurance about their safety. And, for providing this assurance, we have ample capability. The so-called proven technologies, unless subjected to continuous evolutionary improvements, are often a synonym for obsolete technologies.

Basic research is a cultural necessity in any civilized country. The highest intellects in a country must be allowed to work on research problems of their choice. India must also participate in international mega-science projects, which try to seek answers to fundamental questions regarding nature. But basic research, though it gives prestige, cannot by itself create prosperity and security – wealth, strategic strength or societal benefit – without applied research, technology development, high-quality manufacturing skills and R&D-led innovation.

At the same time, we should realize that an advanced technology superstructure cannot be built without the foundation of basic research, including what I have called 'directed basic research', to develop new knowledge and to provide the ability to appropriate knowledge developed in other countries. We should also learn to leverage international cooperation to strengthen our own initiatives. We need 'coherent synergy' (a phrase I introduced many years back[15]) among all the component efforts needed to build a knowledge economy for sustainable development, while laying emphasis on inclusive growth.

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