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Overcoming Challenges of Doing Science in India: A Personal Perspective

Samir K. Brahmachari[1]*

Scope

Science in India has thrived against odds and developed due to individual and collective dreams, passions, perseverance and strategic ingenuity with minimal resources. The article showcases that when leaders dream beyond constraints, nurture young minds, and align curiosity with national purpose, world-class science becomes possible anywhere. The importance of institutional ecosystems, exposure of young minds to the frontiers of science, and a visionary administrative support is highlighted. This "toolbox" offers suggestions for young scientists and policymakers alike to dream audaciously, invest in mentorship and teamwork, democratize technology, build flexible network of institutions and support it with enabling administrative firmament, that facilitates new science and translation of such discoveries into societal good. Success in science lies in the joy of the journey with both passion and compassion, not only in reaching the destination.

Introduction

Over the past five decades, the way of doing science has gone through a major changes, especially in the biological sciences. The advent of molecular biology and the completion of the Human Genome Project have redefined both the scale and the spirit of enquiry. During this period, the Indian economy and science landscape have also undergone a phenomenal change. It transformed from individual excellence under resource constraints, import substitution and economic sanctions to technological leadership. One thing that has not changed is the need to

Author's Address: [1]Academy Professor, Academy of Scientific and Innovative Research (AcSIR) CSIR-HRDC Campus, Postal Staff College Area, Sector 19, Kamla Nehru Nagar, Ghaziabad, Uttar Pradesh-201002

*B101, Karle Zenith Apartment, 100 Ft Kempapura Road, Nagavara, Bengaluru-560 045

Email: skb@igib.in

ask the most appropriate questions and the innate desire to synergistically pursue both individual and collective dreams.

The scientific enterprise has moved from a single principal investigator (PI) driven small laboratory initiative (Science1.0) to mega science, involving many laboratories and diverse expertise, like the Human Genome Project, or the Indian Genome Variation Project (Science 2.0) to the crowdsourcing of knowledge and expertise for projects like Mapping the Human Brain or Open-Source Drug Discovery (OSDD, Science 3.0). We now stand at the threshold of new frontiers (Science 4.0) wherein AI driven tools like Alpha fold 2.0, Chat GPT 5.0 and Google Gemini or IBM Watson will be a part of the research team. We have also entered an era when Nobel Prizes in science, especially in life sciences are shared by scientists for their work done in commercial companies and startups.

This article presents a personal perspective of the author who has been a practitioner and a keen observer of Indian science for over five decades. The key learnings are:

"Dream big, pursue your dream with passion and rest will fall in place".

"Scientific aspirations should exceed the available resources, expertise and technologies".

Science 1.0: In the pursuit of excellence: Building institution, building people

Historically and under the British rule, science was popular in the eastern and southern parts of India and it thrived largely as an individual enterprise. During this era, the nation produced eminent physicists, mathematicians, chemists and clinicians. After a clarion call from visionaries like Shanti Swarup Bhatnagar, Homi Bhabha, Vikram Sarabhai and others, organized science developed and was branded as government science. With the exception of a few institutions, individual-driven science took a back seat. Even under such conditions, excellent individuals in a passionate pursuit of science created their own ecosystems akin in a manner that a silkworm does for itself. The present Indian science and technology ecosystem is the outcome of dreams of a few individuals' and due to governmental support in post independent India [1]. It is noteworthy that the India's first national science institute for fundamental research in basic sciences, the Indian Association for the Cultivation of Science (IACS), was established in Calcutta in 1876 by a private medical practitioner called Mahendralal Sarkar. And, it was here that C.V. Raman did his Nobel Prize winning work.

The Indian Institute of Science (IISc) at Bangalore was established with the support of Sir Jamsetji Nusserwanji Tata in 1908. The subsequent establishment of national laboratories under the Council for Scientific and Industrial Research (CSIR) by Shanti Swarup Bhatnagar during 1946 to 1956 had a substantive support from the Tata Industries. It was this visionary legacy of Jamsetji Tata, carried forward by Dorabji Tata and J.R.D. Tata, that helped create the first set of modern temples of science and technology for independent India.

IISc was dedicated to the pursuit of scientific excellence and to creating future leaders of Indian science. Even after 117 years, IISc still remains the most acclaimed institute for scientific research and education in India. Under the visionary leadership of Satish Dhawan, IISc could attract two of the best minds of Indian science — G.N. Ramachandran (GNR) and C.N.R. Rao (CNR) to establish two world class centers of scientific excellence, Molecular Biophysics Unit (MBU) in 1971 and Solid-State Structural Chemistry Unit (SSCU) in 1976, respectively. The author was fortunate to join MBU in 1974 as a JRF in a CSIR-funded project to GNR and in the following year, he enrolled as a PhD student. He eventually became a Professor at MBU before moving to Delhi in 1997 to establish the CSIR–Institute of Genomics and Integrative Biology (CSIR-IGIB).

It was the influence of GNR and CNR, who singularly focused on scientific excellence, that left a large and sustained legacy of generations of scientists in structural biology and solid-state chemistry. In these areas of research, the Indian scientific contribution is globally recognized. For the author, as a young faculty at IISc, their examples fortified a conviction that world class research in both theoretical and experimental sciences could be done in India, even when the resources were scarce.

Global footprint of structural biology: Biology meets computation

The discovery of triple helical structure of collagen by GNR in 1954 at Madras University could be marked as the first global footprint of post independent Indian Science in Structural Biology. The subsequent discovery of the Ramachandran Map by GNR, C. Ramakrishnan and V. Sasisekharan in 1963 could be considered as the most important fundamental discovery in structural biology from India. GNR moved to IISc in 1971 to establish the MBU. The word unit was considered by GNR to emphasize a small group of researchers and not a department. All the faculty of the unit focused on exploring the structure-function of biopolymers (polypeptides, polynucleotides and polysaccharides) using conformational analysis, X-ray crystallography, biophysical chemistry, peptides and oligonucleotides synthesis, protein biochemistry and molecular biology. Over the next two decades, under the leadership of V. Sasisekharan, MBU became a globally recognized center in Structural Biology. Some of the landmark discoveries here, included the elucidation of the role of hydroxyproline in stabilization of triple helical structure of collagen, the first X-ray structure of type -II beta turn in a linear peptide as proposed by GNR and C.M. Venkatachalam in 1968, the first crystal structure of protein and virus from India, and the structure of peptides with unusual amino acids.

At MBU, questioning established dogma was not a taboo. During the mid-70's, Sasisekharan used a systematic approach to develop a conformational framework for polynucleotide structures to propose that a DNA can have alternate structures other than right-handed double helix. He then proposed sequence dependent left-handed DNA structures in 1978 and the left-handed Z DNA structure was discovered in 1979 in an oligonucleotide crystal by Alexander Rich at MIT. This work created a global impact and provided an impetus for a renewed interest in the study of DNA structures. It was amidst this group in the early 80's, as a young faculty, that the author could establish a vibrant environment to examine the functions of sequence dependent alternate DNA structures both *in vitro* and *in vivo*, and in questioning the idea that repetitive DNA sequences in the genomes are junk and unlikely to have any function.

It is gratifying that the Indian contribution in solving telomere and other unusual DNA structures and role of repetitive DNA sequences in biological function was globally acclaimed and today repetitive DNA occupies the center stage for understanding biological regulation. This demonstrates that a single PI driven initiative in an unchartered path and with limited resources could give rich academic dividends. The development of leadership in structural biology across the institutions in India over the last five decades can be traced back to GNR School at MBU. The story of MBU is well documented by Hari Pulakkat in his book "Space Life Matter": The coming-of-age of Indian science.

Science 2.0: Dream big: When ideas outran infrastructure

It was serendipitous that the author, was present as a visiting scientist in the summer of 1985 at Charles Cantor's laboratory (at the Department of Genetics and Development, Columbia University), when Cantor was invited for a meeting at Washington DC to the idea of Human Genome Project. It was amazing to see how Cantor and other scientists dreamt of sequencing 3.2 billion nucleotides of the human genome in 15 years. This was thought of at a time when the laboratories had limited capacity of sequencing of up to 200 nucleotides in a day.

The author had a first-hand experience of witnessing the excitement of scientists dreaming and imagining of the technologies that did not exist. Realizing the future potential of genomics for affordable healthcare, the author championed the cause by organizing the first workshop on Genome analysis in 1987 at MBU, where Cantor discussed genome sequencing technologies and provided a hands-on training on separation of chromosomes.

Under the Indo-USSR DST-ILTP programme, the author received funding for a project on "Repetitive DNA structure function and chromatin organization". This, in 1989 gave him an opportunity to witness Mirzabekov's laboratory's dreams of creating oligonucleotide chips for DNA sequencing. He had the good fortune to collaborate with them. In 1988, the Human Genome Organization (HUGO) was formed with Charles Cantor and Andrei Mirzabekov as two of the 42 founding council members from 17 countries [2]. To democratize genomics technology, HUGO expanded its membership to several countries and in 1991, the author was the first Indian, to be elected to HUGO membership.

The courage to begin a journey without a map

India then had access to genomics knowledge but did not have the requisite funds for sequencing. The Indian economy was constrained with a severe financial and foreign exchange crisis, and therefore all cost intensive projects such as genome sequencing were ruled out. However, under the visionary guidance of Dr. S. Ramachandran, then the Secretary, of Department of Biotechnology (DBT), and Dr. N. Seshagiri, then the Director General of the National Informatics Centre, in 1986-87 a computational biology program was initiated establishing a Bioinformatics Centre at the Department of Physics, IISc. This was a network of nine centers, prior to the creation of the NCBI at National Institute of Health in 1988. By late 1989, the scientific community began discussing about the risk and benefits of the yet-to-be-launched Human Genome Project (HGP). The author had a privileged access to the planning documents of HGP, from Cantor and these enabled him to foresee the benefits of genomics for India.

On 14th February 1990, Dr. Ramachandran held a meeting at DBT with Charles Cantor (then the Director of the Human Genome Center in California), and Indian molecular biologists including the author, to discuss India's role in the Human Genome Project. The author sent a note for the meeting to Dr. Ramachandran on Genome Analysis. A portion of that note is reproduced below as it became the basis for establishment of "Human Genome—Indian Initiative" under the aegis of the Department of Biotechnology (DBT).

"With the beginning of a national debate on human genome analysis it is necessary to visualise the importance and the limitations of taking up such an endeavor. In the following two pages an attempt has been made to highlight some of the aspects of the human genome project which can have great impact in the national context on biological research per se. While access to primary data is essential for knowledge-based analysis it is also worthwhile to participate and update experimental techniques so as to prepare for the forthcoming new information. This note contains only one's own perception of the problem and how in the Indian context this type of a project could be beneficial" (8th February 1990).

After discussion with Cantor about the 15 years roadmap of HGP, Ramachandran formed an advisory group that included the author to develop the "National Genome Analysis Programme" and sought the opinion of 32 institutions in India. Unfortunately, 90% of the institutions thought genome sequencing technology would be unlikely to have much biology and therefore this initiative did not fructify and India missed the bus to be a part of this mega scientific project that involved scientists from 20 countries (Science 2.0). China was the only developing country that was invited in 1999 to carry out 1% percent of the human genome sequencing.

Seeding genomics in India: Dawn of a new era

DBT initiated the genomics programme as projects in areas, that aligned with national needs. Two projects supported during 1991 were:

- Genome Analysis: Technology development and manpower training at MBU IISc, Bangalore to the author (Rs 2.9 million), and
- Genome analysis of genetic disorders common in India at AIIMS, New Delhi to Prof. I.C. Verma (Rs. 0.6 million).

The project at AIIMS focused on molecular genomic services for known genetic disorders and the author's laboratory explored an unchartered path of triplet repeats associated with neurogenetic disorders and the exploration of genetic markers of schizophrenia and bipolar disorder. This project was in collaboration with clinicians Drs. Sanjeev Jain and Gauri Devi of NIMHANS in Bangalore.

By the mid-90s, economic liberalization started improving the situation for Indian Science. By 1996 with Dr. Manju Sharma as the Secretary of DBT a national document, "Human Genome Indian—Initiative and Genomic Diversity and the People of India" was in place with a budgetary outlay of Rs. 200 million (then $6 million) for 3 years. This was miniscule sum compared to the US annual investment of $200 million for HGP.

During mid-1990's even a simple DNA test for beta thalassemia was not available in India, and samples had to be sent to David Wetherall's laboratory at Oxford for mutation analysis at a formidable cost. Therefore, a DNA diagnostics panel for five most prevalent mutations in India was developed through DNA sequencing at MBU, in collaboration with Dr Geeta Talukdar, RKM hospital, Calcutta. This diagnostic panel was commercialized by M/s Bangalore Genie in 1996 as the first commercialization of genomics knowledge in India.

IISc did not venture into establishing a major genomics center in late 90's, despite, a) MBU nucleating the genomics initiative, b) the presence of a bioinformatics center, and c) major computational capabilities at the Supercomputer Education and Research Center (SERC) at the institute. In 1995, during the formulation meeting of 9th Five Year Plan project at IISc, the author mooted a large project on genomics and molecular medicine. Unfortunately, it was voted out with near unanimity with the argument that "the genome sequencing was a technician's job not quite fit for the intellectual rigours of a top-notch academic institution."

Protecting the Indian genetic resources

Realizing that the large and diverse Indian genetic pool will be important in the post genome sequencing era, in mid 90's, several companies and institutions abroad were collecting samples of patients from Indian hospitals. The author tried to prevent such biopiracy [3] and during 1996 demanded genetic dividend for the contributing patients at various fora of the UN [4]. Consequently, the author was invited to contribute to "The Draft International Convention on the Human Genome" which was adopted by UNESCO in 1997**. India adopted this convention with necessary modification as "National Ethical Policy on

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**Article VI Intellectual property

1. The human genome in its natural state is not subject to private, national or transnational ownership by claim of right, patent or otherwise.
2. Intellectual property based upon human genome may be patented or otherwise recognized in accordance with national laws and international treaties.
3. The collection, distribution and use of human genomic materials and associated information shall be undertaken on a basis which reflects an interest of the original source and of the depositor of the material to an equitable share of the economic benefit of commercialization based upon:
   (a) use of the material and associated information;
   (b) the relative significance and/or unique nature and/or rarity of the genomic characteristic of the material and associated information; and
   (c) the original source and the depositor's relative contributions to the overall creation and commercial development of relevant intellectual property.

the Human Genome, Genetic Research and Services" in 2001 preventing biopiracy.

India in global genomics: When collaboration became a revolution

In 1996, a lecture by Dr A.P.J. Abdul Kalam described the development of India's rocket programme harnessed the collective strength of multiple institutions and industries. This was a visionary model of *Science and Technology 2.0* in action within India and truly inspired the author.

For the International Human Genome Project, India was a vast reservoir of nature's random mutations and a rich repository of biological knowledge. These offered several strategic advantages for understanding the human genome. With nearly a fifth of the world's population and with a tradition of large family sizes, India was an unparalleled resource for genetic analysis, particularly for dissecting complex disorders. The sheer size and diversity of the population also meant that a significant number of rare genetic disorders were likely to be encountered naturally. Furthermore, India possessed a strong foundation of medical expertise (with a large pool of skilled clinicians trained in modern medicine) and an extensive network of hospitals, clinics, and health centers. This infrastructure was exceptional and unmatched by many of the other developing nations. This premise and an ambition for a mega project on "Genomics and Molecular Medicine" took the author to Delhi in 1997 at CSIR-Center for Biochemical Technology (CBT) to establish India's first Functional Genomics project supported by DBT. This involved many clinicians, computational scientists, molecular biologists, geneticists and synthetic chemists dealing with peptide, and nucleic acids. The Indian genetic pool provided a unique opportunity to discover significance of human genome sequences of unknown function through mutation analysis. The idea caught the imagination of fresh PhD's Mitali Mukerji and Beena Pillai from IISc and Debasis Dash from Delhi University who did not have any prior experience of working in genomics. Curiously, it was these first followers, who made India a powerhouse in genomics.

The Functional Genomics Unit at CBT launched two initiatives in 1998 with a support of $2 million from the Department of Biotechnology. These were: a) to initiate genome analysis and understand its correlation with disease-based information available from the hospitals, and b) to develop novel computing and informatics techniques and tools that would help in the analysis of the genomes. DBT also supported projects like *Entamoeba histolytica* genome sequence at the Jawaharlal Nehru University, Delhi; genome diversity projects at the Centre for Cellular and Molecular Biology at Hyderabad, and the Indian Statistical Institute, Calcutta. The Functional Genomics Unit at CBT created network of clinicians and a virtual network institution. This was a dream of Science 2.0, accomplished. A landmark achievement was deciphering the etiology of cerebellar ataxias, from molecular mechanism of triplet repeat expansion to the development of panels of genetic tests (NeuroPro Dr Lal's Pathlab). This was a two-decade long journey comprising three generations of scientists from Mitali Mukerji to Mohd. Faruq, and clinicians Satish Jain to Achal Srivastava from AIIMS Delhi [5].

Bridging silos and building trust

In April 1999 a pharmaceutical company M/s Pfizer India sponsored the development of human resources in pharmacogenomics and genome informatics at CBT to train clinicians. By 2000, India already had the competence to analyze and publish research papers on genome sequences. The first draft of the human genome sequence in 2001, enthused Pharma companies in India to contact CBT with their interest. The first knowledge Alliance "GENOMED" project with Nicholas Piramal India Ltd was thus initiated. The G.N. Ramachandran Knowledge Centre in genome informatics was established through a philanthropic funding from The Chatterjee Group (TCG). After the 9/11 event in the US, 14 BTech Graduates from the Indian Institute of Technology, Kanpur and several students from National Institute of Information Technology joined CBT with TCG fellowship to explore computational genomics. Their efforts led to the development and commercialization of bioinformatics tools PLHost and GenoCluster.

Several of these students moved on to complete their doctoral degree in computational genomics and system biology and are the present leaders in this field, both in India and overseas. By this time, Genotypic Private Limited was incubated at CBT and Strand Genomics (now Strand Life Sciences) was established at Bangalore. From 2001 to 2004, the Tata Consultancy Services joined hands with five CSIR Laboratories and 11 other Indian institutions to build BioSuite, a versatile portable software suite for bioinformatics under CSIR-NMITLI program. Another Science 2.0 initiative [6]. Rarely in Indian science, there has been such a close cooperation between knowledge generation and knowledge dissemination for commercial and social benefit. It established the advantage of being of early movers in any scientific field. In 2002, CBT was renamed as the Institute of Genomics and Integrative Biology. The second genomics institute the National Institute of Biomedical Genomics was established in 2009 at Kalyani in West Bengal.

Science 2.0 Genetic landscape of the people of India: A canvas for disease gene exploration

In the 10th Five Year Plan (2002-2007), CSIR created provision for a large funding for network projects in genomics like the Indian Genome Variation Project and *In Silico* Biology for Drug Discovery.

The International HapMap project was started in October 2002 to map global genomic variation in the human genome by drawing samples from diverse populations [2]. India had the option of joining this by contributing 30 samples or to initiate its own Indian Genome Variation (IGV) project. CSIR-IGIB chose the second option because the Indian genomic diversity could not be adequately represented in mere 30 samples. The international HapMap project decided to collect 270 samples from four populations (YRI African, CEU European, CHB Chinese and JPT Japanese), with a budget of $100 million. Concurrently and with a budget of $5 million, the CSIR-IGIB led Indian Genome Variation (IGV) Project analyzed 1,871 individuals, from 55 populations (32 large and 23 isolated). This was by strategically designing the experiments and involving five other CSIR laboratories (CCMB, CDRI, IICB, ITRC & IMT) and Partha Majumder from the Indian Statistical Institute [7]. The challenge was to coordinate with 24 Principal investigators, (unfamiliar to each other and without an experience of working in large consortia) assisted by a hundred students and technical assistants. Many technicians from The Center for Genomic Application (TCGA) also worked in this initiative. The TCGA** facility provided services to many smaller laboratories across the country who could not afford expensive equipment for genome sequencing and genotyping.

The key to the success of the IGV Project was the decision to entrust its project management and experimental coordination to two younger scientists at CSIR-IGIB Mitali Mukerji and Debasis Dash who led, respectively, the experimental and data management components. of this massive national effort. By 2008 a landmark paper with 150 authors, “Genetic landscape of the people of India: a canvas for disease gene exploration” was published. This heralded India’s arrival as a noteworthy serious contributor to genomics [8]. Again, this was Science 2.0 realized.

This work provided the first comprehensive genetic map of the diverse Indian population and identified predictive markers for complex diseases and pharmacogenomic studies. Consequently, HUGO invited

** TCGA was first of its kind publicly owned privately managed core shared genomics facility, a collaboration (2004-9) between CSIR-IGIB and Institute of Molecular Medicine, a not for profit entity of The Chatterjee Group.

India to host the International Human Genome Meeting 2008 with the author, member of the HUGO Council, as its Chair. On author's invitation, Lalji Singh and Partha Majumdar joined this effort as Co-chairs.

The Indian Genome Variation Project was a collective effort and laid the foundation for coordinated projects in genomics in the country. In 2005 India was invited to join the PanAsia SNP project involving 10 Southeast Asian countries including HGP participants Japan and China [9]. These studies established that the genetic makeup of the population of India encompasses the diversity of the world and makes it an ideal setting for disease genetics, pharmaco-genomics and clinical trials. Genetically therefore India is seen as representative collective of global population as visualized by the great poet Rabindranath Tagore in his poem "Bharatatirtha" ("The Indian Pilgrimage") invites all of humanity to Indian shores, seeing the nation as a land of unity and vast humanity.

From lone warriers to synergistic research ecosystem

CSIR-IGIB kept pace with global genomics by 2009 when it sequenced the first Indian human genome. Subsequently by 2021 "IndiGenomes: a comprehensive resource of genetic variance from over 1000 Indian genomes" was completed [10]. Presently, with the support of DBT, the national effort, the "Genome India project" has completed 10,000 human genome sequencing from 83 populations in 2025 [11]. This study, leveraged insights from the Indian Genome Variation Project to identify populations that best represent the diversity landscape of India. The recently launched "Phenome India" project of 10,000 CSIR cohorts is a unique Science 2.0 initiative. It is gratifying to see how far we have come in genomics technology in India. In 35 years, a dream became a reality and empowered Indian healthcare providers with data on Indian population. This has indeed been a long and challenging but satisfying journey.

Economic impacts of genomics in India

The availability of indigenous technology, skilled workforce driven by advancement in clinical genomics has implied a growth of the Indian genomics market through its helping with cancer screening, testing of rare diseases and in personalized medicine. The Indian genomics market size was at $2.2 billion in 2024 [12] and its projected to reach $9 billion by 2033 at a CAGR (Compound Annual Growth Rate) of 16.1%.

Clinical genomics, oncology, prenatal testing and pharmaco-genomics are the key segments driving this growth. From two startups in the year 2000 focusing on genomics, the number has crossed 1000 in 2025. Now over 400 clinical laboratories in India have adopted genomics in clinical practice [12]. Almost 10,000 people are employed in genomics-related work with 40% in wet labs and 60% in bioinformatics. The vision of 1998: "*In this scenario it is imperative that Indian scientists, medical practitioners and pharmaceutical industries should come together to develop the necessary expertise and utilize our rich genetic wealth to convert it into economic wealth*" has been realized.

Science 3.0: Open-source drug discovery: Linux for pharma

The CSIR network project "*In Silico* Biology for Drug Discovery" identified and patented several novel non-active site drug targets for *M. tuberculosis* but none of the large pharma companies were interested in exploiting that knowledge, given that the market size for tuberculosis was only $300 million. Although the *M. tuberculosis* genome sequence was made available by Pasteur Institute in 1998, 60-year-old treatment continued and 4000 TB patients died everyday across the world. Nearly, 25% of the deaths occurred in India. It was therefore realized that a system biology level approach is needed to develop non-toxic drug targets, that are affordable. Strong intellectual property increases availability but compromises affordability. Inexpensive discovery needs open innovation and shared wisdom. Inspired by the open-source model in information technology, like the Linux, the Open-Source Drug Discovery (OSDD) project for Tuberculosis was conceptualized in 2007 and launched in 2008 as a Team India project with global participation led by CSIR [13]. The project was met with a significant skepticism nationally, however eminent scientists like William Hesseltine, Bernard Munos appreciated and encouraged the author to take it forward. The concept was to collaboratively excavate and aggregate the available biological and genetic information of *M. tuberculosis* that lies buried in literature to hasten the drug discovery process using the system biology platform. By 2010 *M. tuberculosis* genome was annotated as a virtual community effort through crowdsourcing of 800+ students and researchers. This Connect to Decode initiative mined 45,000+ publications and achieved a 99.5% annotation of all the genes. This was Science 3.0 in action and it was accomplished at a time when working in virtual space was not even heard of [14]. By 2013, the OSDD had provided an unconventional global scale virtual collaborative platform for discovery of new drugs for tuberculosis using computational to experimental chemistry. OSDD became a distributed virtual laboratory with over 8700 participants from 130 countries and became the largest crowd-sourced scientific project in the world, attracting global attention, with extensive coverage in the literature [15, 16]. Hence not discussed further in this article.

By 2015, the OSDD programme was subsumed into the Indian TB Research and Development Consortium (ITRDC) project led by Indian Council of Medical Research, which created novel method of asset utilization and capacity building at a negligible cost, leading to positive economic impact [17]. The OSDD programme is now an integral to the development of the national intellectual property rights (NIPR) Policy 2016 and it has been accepted as a model for neglected disease drug discovery by WHO.

OSDD has now gone global. The power of open source was amply demonstrated during the Covid-19 pandemic and many open-source projects were initiated. In 2019, the Tata Trust established the Open-Source Pharma Foundation in Bangalore to take OSDD initiative forward. Today, a major Science 3.0 initiative is the crowdsourcing of mapping the human brain. Surprisingly, the Indian scientific community, despite a large student community has not initiated crowdsourcing projects. On introspection it seems, we as a community need to develop chutzpah to do things differently, despite the skepticism every novel initiative encounters.

Science 4.0: AI enabled: Affordable and quality healthcare

The World Chess Championship 2024 has shown the acumen of the young Indian mind. Boys and girls now are world champions at the age of 18 when their inspirational leader Viswanathan Anand had similar accomplishments only at age 30. Power of crowdsourcing of young mind is amply demonstrated in the previous section. Despite phenomenal technological development in life sciences in India, the average life expectancy increasing from 32 to 72 since independence, affordable quality healthcare for all still remains a distant, elusive dream. Availability of large number of human genome sequences along with clinical information and other multi-omics datasets hold the key to curative and preventive affordable quality healthcare of the future. However, this needs properly orchestrated, genuinely synergistic effort by professional scientists and medical practitioners alongwith AI startups and thousands of high school and undergraduate (MBBS, BTech, Biotech etc.) students with expertise in using AI tools can contribute effectively.

Science 4.0 will have all the elements of Science 3.0, including crowd sourcing the talent plus the new AI tools like Chat GPT 5.0, Google Gemini, Alpha Fold 2.0, and IBM Watson as research assistants. Indian scientific leaders need to utilize talented young minds in such data-driven, citizen science. Learning by doing, will be the new norm of the future education and in this, gifted GenZ Indians would need to lead.

The catalytic and leadership role of INSA

The Indian National Science Academy should spearhead this movement in the country by formulating policy and creating opportunities for capacity building and participation of the young generation. It should establish a working group of fellows with complementary expertise to create a vision map and implementation strategies. In the biology/pharmaceutical realm this will allow creation of a road map for the development of AI agents to identify novel biomarkers specific to the Indian population for wellness; identification of biomarkers of early onset of non-communicable diseases in the Indian population; AI tools for repurposing FDA approved drugs for different diseases based on biochemical pathway analysis and through a system biology approach. Equally important is the development of predictive AI tools for identifying adverse drug reactions and drug–drug interactions, enabling personalized preventive healthcare through recommendations on diet, lifestyle, and wellness interventions. Integrating traditional knowledge–based systems such as Ayurveda with modern biomedicine can pave the way for the holistic medicine of tomorrow. The vision should be to build *Developed-in-India Healthcare AI Agents* that are trained on data of Indian population, reflective of its diversity. This will not only serve Indians but also the broader reals of developing world with affordable, high-quality, and contextually relevant healthcare solutions. This will be science diplomacy for global good, at its best.

Way forward: Science and technology for nation building through career building

By the time this article reaches the Indian scientific community, the newest AI Scientist, *Kosmos*, will likely have arrived. This new generation of AI systems will not only read and comprehend vast volumes of literature but also make novel discoveries. In such a landscape, imagination and wisdom will become more valuable than mere knowledge. These will be the true fuel for disruptive innovations.

How should the Indian scientific community prepare itself to contribute to science and technology aligned with national goals? In 2024, India emerged as the third-highest contributor to scientific publications worldwide (as per the Web of Science Index) and also ranked third in the top 10% of highly cited articles spanning applied, physical, and life sciences. The challenge before us now is to translate this high-impact research into innovations that yield tangible economic and societal returns. To achieve this, the Science and Technology Departments of the Government of India, along with the Academies of Sciences and Engineering, must together create a blueprint for the science and technology of the future.

One that leverages India's natural resources and traditional knowledge base, offering a strategic advantage over other nations.

This vision must be driven by young, talented scientists and not left to only seniors, as they will be the future leaders of Indian science and technology and should take up ownership of emerging this landscape. It is important to remember that vision is not transferable, dreams belong to individuals, and a leader is, above all, a seller of dreams. Future discoveries and disruptive innovations will arise at the interfaces of disciplines, demanding new organizational structures and a newer model of leadership and dynamism.

The ongoing shift from the industrial age to the knowledge age, accelerated by the information technology and AI revolutions, calls for organizations that have:

- Flexibility to take on emerging challenges,
- The ability to harness multidisciplinary expertise,
- Mechanisms to reduce the time from concept to implementation, and
- Agility in building new skills through networking and crowdsourcing talent.

Only such organizations will survive to be the major players in the globally competitive frontiers of science and technology.

A successful model already exists in the Academy of Scientific and Innovative Research (AcSIR), the world's first virtual university established to create transdisciplinary human resources without additional capital investment. Similarly, India needs to create virtual laboratories and networked organizations to explore new frontiers and establish leadership in niche areas such as biomimetic materials, advanced manufacturing technologies, industrial synthetic biology and green chemistry, institute of sustainable engineering, etc. These can be achieved by drawing expertise from national laboratories, university departments, industrial R&D units, and startups to undertake challenge-driven projects.

Young faculty must be mentored and empowered to tackle bold, high-impact problems and evolve into future leaders of Indian science and technology. Tomorrow's leaders must be deep domain experts with a broad cross/interdisciplinary understanding, capable of integrating insights across fields and envisioning the future. We must nurture scientists who are problem-solvers with a passion for discovery and not content with incremental science or copycat technologies.

Funding agencies should encourage high-risk, innovative ideas at the cutting edge of science and technology, and reward ambition over guaranteed success. To make this possible, our scientific audit system should be restructured and success metrics must be defined at the time of project sanctioning. Experience shows that industry funding readily follows innovative and purpose-driven ideas.

Our reward and award systems also need rethinking. We must move beyond recognizing only individual excellence to acknowledging the collective achievement of teams and the impact of their work. This would allow multidisciplinary collaborations to be duly recognized, enabling multiple scientists to share honors such as Academy Fellowships or National Awards. Such a shift will remove the current disincentives for collaborative research.

If India is to become a developed nation by 2047, we must apply high-level science and technology to ground-level problems. Let us conclude with the timeless, sage words of Mahatma Gandhi, spoken at IISc on 12 July 1927:

"Just as some of the experiments in your laboratories go on for all the 24 hours, let the big corner in your heart remain perpetually warm for the benefit of the poor millions."

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SAMIR K. BRAHMACHARI is recognized for his pioneering contributions to genomics, structural biology and system medicine. He obtained his PhD in Molecular Biophysics from Indian Institute of Science, Bengaluru. Prof. Brahmachari served as Director General, Council of Scientific and Industrial Research (2007-2013) and as Founder Director of the CSIR-Institute of Genomics and Indicative Biology (1997-2007) where he pioneered functional genomics research and established the Indian Genome Variation Consortia, a landmark initiative mapping the India's genetic landscape. Prior to that he was a professor at Molecular Biophysics Unit, IISc. He is founder of the Open-Source Drug Discovery (OSDD) program, a global collaborative platform for developing affordable drugs for neglected diseases such as tuberculosis. His work emphasizes open innovation, integrative biology and translational research for societal impact. He is recipient of several national and international awards including INSA Young Scientist Medal, Shanti Swarup Bhatnagar award and the HUGO Chen Award for distinguished academic achievement in human genetic and genomic research. He is a Fellow of all four National Science and Engineering Academies, The World Academy of Sciences (TWAS) and European Society of Preventive Medicine, UK. He continues to promote science-driven entrepreneurship by mentoring startups in genomics and digital health. He founded Sahaj Path Knowledge Foundation an EdTech platform for educational support for rural school children.