Science and mega science: a perspective

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The need for pursuit of science arises from the innate curiosity of human beings, making them wonder, deliberate and learn. Natural sciences observe nature across different scales and the knowledge acquired is often used for the benefit of mankind through technological applications. Study of nature at extreme scales always pushes the existing limits of technology, and has made it necessary that governments across the world pool in their human and other resources through international collaborations. The wide participation of India in large international projects, mega-science projects, is highlighted in this article. The sociological and scientific need and implications for the participation of our country are also discussed.

Keywords: Collaborative research, extreme scales, international projects, mega-science.

THE scientific research carried out collectively by a large number of people across geographical and cultural boundaries in pursuit of a common goal is termed here as mega-science, and the projects planned and executed in its pursuit are called mega-science projects. Let us first dwell on the attributes of science and the need for it.

The *Oxford Dictionary* defines science as 'The intellectual and practical activity encompassing the systematic study of the structure and behaviour of the physical and natural world through observation and experiment'. Notice that empirical observation is an integral part of science. Such is the need of experimental verification of an idea to be termed as science, that even Einstein's theory of relativity was not considered worthy of a Nobel Prize. One of the members of the Committee, an ophthalmologist, who was awarded the Nobel prize 'for his work on the dioptrics of the eye', noted for the theory of relativity that 'the effects that are measurable with physical means are, however, so small that in general they lie below the limits of experimental error'[1]. The main criticism of the 'theory of everything', the super string theory, is its inability to provide a falsifiable hypothesis that can be tested by designing experiments using the present-day technology to probe nature. This also underlines the fact that the results of deductive science also need to be verifiable by experiment. The onus of providing a hypothesis of falsifiability and/or confirmation to test the validity of the theory by experiment, lies with the propounders of the theory.

The first observations of nature were those which were perceptible to the naked eye. The knowledge derived from the observation of nature is used for the well-being of humanity, and is a natural progression. Thus also developed, new fields of applied sciences. The popularity of applied sciences increased and along with it increased the cognizance of the role of pure science research as the root of most applications. Pursuit of science as a discipline commanded respect in society, as is also evidenced by the support of governments across the world. The desire for acquiring knowledge for the sake of knowledge, an entitlement and a privilege of human beings, led to a systematic effort to observe nature using tools other than the naked eye.

Aristotle, in about 340 BC, was the first to emphasize the need for observation in scientific knowledge. Observations in astronomy have a history of more than a 1000 years, with indirect evidences from much earlier times in the world. The practice of systematic study to observe and draw conclusions was presumably first done by Galileo, establishing a method of science that is still in vogue. While there may be many claims of such sporadic activities, Galileo's efforts are recorded in history to be amongst the most significant, setting the present scientific method and thought.

Why should we 'do' science? Human beings are endowed with a mental faculty to question what they observe and seek answers. The complexity and the scale of nature is so wide that it offers numerous possibilities to human beings to study nature. The knowledge accumulated over a period of time branched into different disciplines, depending on the scale at which nature is being observed.

Science at different scales

One attribute that distinguishes the different disciplines that have emerged from the observations of nature is the 'length scale'. While cosmology and astronomy are studied at a scale of 10^{+20} m, particle physics observes

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nature at the 10^{-20} m scale. All other disciplines of science fall within this range and have developed specialized tools and methods at different scales, allowing for regions of overlap. More the departure of the scale of observation from what is observable to the human eye, greater is the need for specialized tools. Each new phenomenon discovered, new law understood, new technology developed provides a platform for the next level of understanding nature: a new discovery, a new development.

Biological sciences presumably started as observation of nature at a scale comparable to, or within an order of magnitude, the size of a human being, termed here as the 'normal' scale. The naked eye could observe living organisms using this normal scale. Starting with a study of animals and plants, the biological sciences diversified to study microorganisms which can affect life. This makes biological sciences of widespread interest and use, as is also evidenced from the number of people working in this discipline. Probing organisms in nature at a deeper scale now requires some of the most powerful microscopes for observation.

So why pursue science at scales vastly different from those that have great relevance to human beings, e.g. biological sciences? Research at extreme scales provides an intellectual challenge. Experience has shown that the offshoots of such intellectual pursuit have also provided unexpected dividends for mankind, the World Wide Web being one of them[2]. Such intellectual pursuit is often demanding, requires a lot of training, and yields knowledge for its own appreciation. Some notable offshoots of research in pure science are the discovery of X-rays, the use of which was imminent; the idea of electricity and invention of light bulbs, and in the more recent times, the application of Einstein's 100-year-old theory of relativity in the global positioning system (GPS) used in our cell phones[3]. The two World Wars, particularly the Second War, are replete with examples where the knowledge of science was used to make strategies and weapons, which led to the final outcome in the wars. Research in science supported the industry. It is good to recall that the desire for acquiring knowledge for its own sake, without looking for immediate applications, has resulted in all the technological development that we see today.

Nature does not reveal its secrets easily and new discoveries are likely to become increasingly difficult. This might be either due to the subtlety of nature, or due to the immense departure from the 'normal'. The extreme scales are the less explored regions, and provide new perspectives – both the expected and the unexpected. Studying nature at the edge of the existing knowledge is often a daunting task due to the expertise required, besides being financially beyond the limited resources of most countries. It is therefore essential for different groups with varied expertise from different countries to collaborate, in order to make these experiments possible. The nature of the large-scale collaborative research transcends all geographical, political and cultural boundaries, just as science is not limited by boundaries.

Indian participation in mega-science projects

It is now a question of the past whether India should participate in mega-science. The country has actively participated in many mega-science projects, according to a report of the Department of Science and Technology (DST)[4] of the Government of India. Indian participation in mega-science also justifies her contributions to science over the last many decades. Some of the more prominent mega-science projects with Indian participation are mentioned below. Personal experience and bias have led to particle physics being discussed first. Some of the features mentioned while describing experimental particle physics, may be relevant in other cases also.

Particle physics

Experimental particle physics is a discipline that probes the structure of matter at the smallest scales by bombarding it with high-energy particles. The scale of 10^{-20} m requires very large energies. The Large Hadron Collider (LHC)[5], a marvel machine at CERN, Geneva, is able to accelerate particles to 0.999999990 times the speed of light. The design and implementation of the LHC required decades of efforts of many scientists and engineers. One of the major components in the construction of the LHC are superconducting cables. It may be worth ruminating that superconductivity was discovered more than a century ago, in pursuit of understanding properties of materials at low temperature, oblivious of its probable use in a machine to be conceived, designed and used in subsequent decades, and is an example of science and technology feeding each other for progress.

The experiments at the LHC probe the properties of matter at 10^{-20} m by colliding particles (and nuclei) at very high energies. What emerges from each of these collisions is unique to the collision and is captured by a large number of particle detectors, each of which acts like a high-speed, high-resolution camera. While each collision is unique, they follow a certain pattern which is governed by the laws of nature. Deduction of these patterns and the subsequent laws requires the concerted effort of many.

Capturing millions of images and recording them for future purposes makes demands on the speed at which this is achieved. Each of these detectors requires years of expertise and (super) specialization on the different aspects of detector technologies. The speed and amount of data stored for further studies require the use of latest techniques and tools in electronics and computing, while pushing the limits in both of them. Whether the new tools developed for quick and precise measurements transform into useful devices for mankind will be known only over a (long) period of time, and should not be a prerequisite for pursuing fundamental research.

The variety of tasks like design and fabrication of the detector, its mechanical arrangements, reading the signal out, processing the signal and recording it for pattern recognition and/or conformity with existing patterns, each requires a large number of people with varied expertise. This makes the whole effort collaborative, requiring greater and greater specialization, and hence the number of people increases. CERN is a remarkable example of a collaboration at large scale, an example worth emulating. The Indian participation is from many educational institutes, including Universities, IITs and research institutes and is funded by the DST and the Department of Atomic Energy.

The Facility for Antiproton and Ion Research (FAIR) in Germany is another major mega-science project in the field of particle physics, with a large Indian contribution and participation. There are four major experiments under planning at this facility, addressing various phenomena of physical sciences across scales, from atomic and plasma physics and their applications, to compressed baryonic matter, nuclear structure, astrophysics and others[6].

Laser Interferometer Gravitational-Wave Observatory

There never has been any doubt among the scientific community about the correctness of Einstein's general theory of relativity (GTR). Advances in technology made GPS possible, an application on most mobile phones. The determination of position requires the use of equations of GTR, something not envisaged by Einstein a 100 years ago. GTR also predicted the existence of gravitational waves that produce strain in space–time. It was imperative for the curious human mind to observe these waves. Like for most mega projects, initial efforts and attempts to set up an experiment to detect gravitational waves underwent gestation and hiccups, and eventually commenced in 2002 as the Laser Interferometer Gravitational-Wave Observatory (LIGO)[7].

The major challenge of the experiment was observation of a strain in space–time, which is smaller than the size of a proton. The experiment reported success in 2016, 100 years after gravitational waves were predicted. The source of these waves was an event that happened 1.3 billion years ago, and its measurable effect was observed on earth, providing direct confirmation of the existence of gravitational waves. It may be noted that the age of the universe is ~13.7 billion years, according to current scientific wisdom. Simultaneous observations of the gravitational waves in experimental set-ups separated by thousands of miles, help in localization of the source of waves. This may well be the new tool of astronomy – gravitational wave astronomy to probe the deeper layers of the sky. As part of the Indian participatiion, an advance LIGO detector will be installed and integrated in the network of other detectors in USA and Italy. India becoming a part of the LIGO scientific collaboration is an appreciation of the efforts of our colleagues, and a commitment to pursue science at extreme scales. The requirements of precision for the experiment will set new standards for the industry. 'It is for the later liasion that can extract the benefit from the industry in future'[8].

ITER[9]: Fusion device for energy

Stars in the sky, including the sun, are also wonders of nature with their apparently endless supply of energy. The source of this energy was identified as fusion of hydrogen into helium, where the large binding energy per nucleon of the helium nucleus caused a decrease of mass and hence release of energy in fusion. There is an imminent desire to use the 'principle of energy creation in stars' for creation of energy for the benefit of mankind. The idea took the name of 'controlled thermonuclear fusion', now a well-understood science. However, recreating the processes in a controlled manner requires emulating conditions akin to what is present in the stars.

The device being designed for the purpose is called a tokamak (an acronym in Russian for a device to contain plasma). This requires overcoming a number of technological issues for controlling high-density plasma at extremely high temperatures, more than 10^7°C, which facilitates fusion. The challenge is to contain the high-temperature plasma without letting it come in contact with the walls of the container, and yet use the energy to generate electricity. The Indian experience of making a medium-sized tokamak, Aditya[10] at the Institute of Plasma Research in Gandhinagar, Gujarat, has led to the country's participation in the international project ITER. The mega nature of the project of harnessing energy from fusion has already initiated research into the next project after the projected completion of ITER, and is called DEMO[9].

Human Genome Project

One of the most wonderful creations of nature is the human body. In pursuit of the study of nature, humans now understand the working of a body. As has been in the nature of science, this understanding has to probe deeper, and look for patterns that may exist in this miracle of nature.

The building blocks of the human body are the cells that contain DNA that is unique to each individual. The identification that uniqueness of an individual is present in the basic structure of her/his body and is coded in the

DNA, is a major achievement of the human mind. The science of genetics progresses by sequencing and mapping of the human genes with their physical and functional properties. Sequencing the extremely large number of base pairs ($\sim 10^9$) was a daunting task and could be completed only because of the large-scale participation of many collaborating institutions in the Human Genome Project (HGP), another international mega-science project. The classification of tens of thousands of genes in a human body, and their identification with possible diseases, initiated research into gene therapy.

The success of the genome project (now called HGP-read) has led to the new HGP-write Project, where attempts would be made to construct human genes from bases in order to understand and control the functions of each gene. Unlike most other pure science mega projects, the applied nature of the Genome Project had a quick return on investment by generating more than 50 times the investment of about 15 billion USD, and millions of job years of employment[11]. Many institutions in India now participate in the Genome Project and one of its variants, with liberal support from the government. Collaboration with the Anthropological Survey of India (ASI) has contributed to the identification of indigenous diversity in the country.

While the science and the resulting technology of the HGP are a boon to mankind, more knowledge often creates more options, not all of which may be desirable. One such undesirable option is to use genetic structure as the reason for actions of a human being to make judgments. Further, modifying specific genes to change the natural behaviour may also have other avoidable effects, even though this may be useful in medical applications. The ethical issues pertaining to this are more related to cultural, sociological, moral and political matters, and are outside the scope of this article. However, to meet the ethical issues, it is imperative that the advances in science should not be in isolation, and require an increased awareness, outreach and education programme for the society.

Thirty Metre Telescope

The visible part forms only about ~4% of the actual universe. The rest is made up of invisible or 'dark' matter and energy, the presence of which has been deduced from information on gravitational pull on the galaxies and the bending of light. This dark energy is also responsible for the expansion of the universe at the time of the big bang. Looking deeper into space allows us to look back in time and hence study events closer to the birth of the universe. The Thirty Metre Telescope (TMT), a ground-based telescope to be built in collaboration with CalTech and University of California (USA), Canada, Japan, China and India, will enable us to find answers to questions regarding the nature of dark matter and energy[12]. The telescope has a huge light-collecting ability over a large range of wavelengths, which gives it a high angular resolution.

Indian participation in the TMT project would give Indian scientists an opportunity to work in an international facility with world-level technology, which would not be possible at the national level due to prohibitive costs. Like in most other collaborations, Indian participation in the project is through in-kind contributions. This provides an opportunity for the Indian industries to engage in new technologies which are demands of frontline research. In addition to contributing to the future growth of astronomical telescopy in India, it is up to the industries to use the new technology for further development.

The sociological effect

Because of the sheer nature of mega projects and international collaboration experiments, the required efforts are big, the stakes are big and the rewards are big. The discovery of the Higgs boson, popularized by media as the 'God particle', has increased awareness amongst lay people about CERN. The efforts into the new technologies and the success of such efforts have resulted in CERN being a recognizable 'brand' name associated with excellence in scientific endeavours. This excellence has been achieved by overcoming major technological and intellectual challenges, and continues to attract the best minds in the world to work at CERN. Similarly, the discovery of gravitational waves by LIGO has raised curiosity amongst the masses as well as high-school students with impressionable minds, about GTR.

Excellence in research requires commitment and excellence in work-culture, work-ethics and work-quality, the result of which is often seen in the output. In collaborations with large number of people with unassigned responsibility and freedom to contriute to the extent of their expertise, the effect of beneft of above mentioned attributes to the collaboration is often veiled. As the size of a collaboration increases to include people from diverse expertise and cultures, the complexity of socio-political issues increases, as in any other large organization. This has necessitated the collaborations to make their own constitution and working principles. It requires the wisdom of the scientists to overshadow political and personal reasons in favour of academic arguments in decision-making, in the interest of academic and intellectual growth.

It is true that society acknowledges 'proof-by-association'. People who are associated with projects at CERN are often considered in awe because of the 'brand' name. So there is a need to define accountability of individuals working in large collaborations. On the one hand, the efforts of some are hidden to the outside world in a large collaboration. On the other hand, there are free riders who unashamedly encash their association with the collaboration in the outside world. The collaborations may need introspection to address some of the issues mentioned above in the long-term interest of the collaborative research culture to remain healthy.

Participation, involvement and commitment

Considering that mega-science demands many more resources over a long time, the average resources required per participating person is probably higher compared to some other disciplines at not-so-extreme scales. For a country like India limited by resources for research allocation, one often introspects about the utility of mega-science projects.

It is justified to ask 'who should spend money for science at extreme scales?' Should it be the developed countries, developing countries, Western democracies or Eastern powers? We also need to ask, 'Whose responsibility is it?' To address this question we need to understand who will benefit from the fruits of this labour. That answer is simple – mankind. Hence it is the responsibility of mankind to pursue this science. CERN is an excellent example where the contribution from various countries is related to their gross domestic product (GDP).

We should neither create artificial boundaries for the study of nature, nor limit the research in the hope for breakthroughs. The discovery of Higgs boson, deconfined state of nuclear matter, and gravitational waves were the results of planned projects with some specific goals. Research in science at extreme scales is going into uncharted territory – we might discover a lot or may not discover anything new; there might also be 'Eureka' moments. In certain scientific research that often tests hypothesis, whether the result is positive or negative, in either case we advance our understanding of nature. We cannot be parochial and limit ourselves to applied science or technology, even though its importance can never be overstated. Applied research is motivated solely by the immediate application and hence its relevance is transparent to all. But all applied research is based on knowledge created and collected through fundamental research.

Over the last few decades, India has successfuly paved the way for its people to participate actively in mega-science projects. It is because of this reason that India is now committed to many such projects[4]. For the present and the next generation, the community has to be provided continuous support, not just to traverse the path paved in the previous decades, but also by removing any possible hurdles that may arise in the journey. A significant contribution at the international level requires continuous long-term efforts demonstrating acquired experience and expertise. While respecting the public money, all efforts should be made to enhance the benefit from international participation to our countrymen, in all possible ways. Let us work collectively to achieve perfection asymptotically, while training and educating the very rich demographic dividend available to us, in their interest and in the interest of the country at large.

Bob Wilson (the first Director of Fermilab, USA) was asked by a Congressional committee, 'What will your laboratory contribute towards the defense of the US?' He replied 'Nothing, but it will make it worth defending (thanks to Atul Gurtu for this anecdote)'. Let us remember that every 15-year-old is mesmerized by what she/he sees in the sky, and around. We need to pursue science in the country, at all scales, to make life interesting and worthwhile for them, and hence for the country. A civilization like India has to increase its focus and spending in the pursuit of science, and expand what it learns to technology.

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