Doing science as a way of life*

C. N. R. Rao

Scientific pursuit is essentially a creative urge. Science is also an important part of our culture. Science is a demanding master, not easy to satisfy. Only those who completely submit to it seem to reap the benefits in terms of intellectual excitement and satisfaction. In this context, it is beneficial to recall the lives and work of great men who accomplished against all odds and would not give up easily. What is also wonderful is that there is no limit to scientific pursuit. It is thrilling to witness the way ideas which start off as a mere grain of pollen develop to become forests and continents. Nothing can be more rewarding to a scientist than achieving a state where doing science becomes a way of life.

BERNAL wrote many years ago that 'Man is occupied and has been persistently occupied since his separate evolution, with three kinds of struggle: first, with the massive unintelligent forces of nature, heat and cold, winds, rivers, matter and energy; secondly, with the things closer to him, animals and plants, his own body, its health and diseases; and lastly, his desires and fears, his imaginations and stupidities'. I cannot improve on Bernal's statement, but it is my feeling that whatever be his struggle, the thinking man has always exhibited the distinct characteristic of compulsive occupation with unfettered intellectual explorations to satisfy his philosophical urges. Science is one of those urges. In social science usage, the term 'Science' denotes the systematic, objective study of empirical phenomena and the resultant bodies of knowledge. According to this definition, many disciplines related to social sciences should also come under Science. Science as a human activity is itself a subject of social science investigation. One must admit therefore that as an intellectual effort, science cannot be regarded as something apart. It is an important part of our culture. Science permeates our thinking today and it would be unimaginative to completely separate it from what we normally refer to as humanities and social sciences. Natural science does not simply describe or explain Nature. It is a part of an interplay between Nature and man. As Heisenberg stated 'Science describes Nature as exposed to our method of questioning'. One aspect that distinguishes science from other scholarly pursuits however is that much of science is based on experimentation.

It is not my purpose to discuss the nature of science or of scientific thought here. Neither am I going to dwell on science and humanism or spirituality. There is much written about such matters by wiser men. I shall concern myself with those aspects of science and scientific pursuit that are necessary for the purpose of this presentation, which deals with doing science as a way of life. In such an endeavour, I shall make use of the thoughts of great personalities who have contemplated about these matters, besides recording my personal reflections. Before I proceed with the theme of my lecture, I would like to briefly mention some of those aspects of science that have made great impression on me.

Some features of science

Imagination plays a vital part in science, but has certain constraints. As stated by Feynman, 'whatever we are allowed to imagine in science has to be consistent with everything else that we know... We cannot allow ourselves to imagine things which are obviously in contradiction to the known laws of Nature. Our kind of imagination is quite a difficult game. One has to have the imagination to think of something that has never been seen before, never been heard before. At the same time, the thoughts are restricted in a straight jacket, so to speak, limited by the conditions that come from our knowledge of the way nature really is. The problem of creating something which is new, but which is consistent with everything which has been seen before, is one of extreme difficulty'. At the same time, the difficulty with science is often not with the new ideas, but in escaping the old ones. A certain amount of irreverence also seems to be essential for creative pursuit in science.

Science does not allow exceptions. Without this feature, there would be no determinism in science or there would be no science at all. Another interesting

*Based on the G. P. Chatterjee lecture on 'Science and Man', Indian Science Congress, Goa, 1993.

C. N. R. Rao is in the Indian Institute of Science and Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore 560 012, India.

feature is that 'full explanations are often seized in their essence by the scientist long in advance of any possible proof'.

Unanimity of opinion is not necessary in science. While unanimity of opinion may fit a religious organization, a variety of opinion is absolutely essential in science. Science is the only area which has not produced sects (although there are disciplines and schools in science). It is founded on analysis and synthesis. It does not occupy itself with probable truth. More importantly, it has the same method in all parts of the world. In questions of science, as Galileo said long ago, 'the authority of a thousand is not worth the humble reasoning of a single individual'. 'Freedom is the first-born daughter of science' as Thomas Jefferson put it. Yet, there is no democracy in science. We cannot say that some second-rate person has as much right to opinion as Einstein or Pauling. It is useful to remember the motto of the Royal Society, 'Nullius in Verba' (we do not take anybody's word for it).

Jacob Bronowski has written, 'By the worldly standards of public life, all scholars in their work are, of course, oddly virtuous. They do not make wild claims, they do not cheat, they do not try to persuade at any cost, they appeal neither to prejudice nor to authority, they are often frank about their ignorance, their disputes are fairly decorous, they do not confuse what is being argued with race, politics, sex or age, they listen patiently to the young and to the old who both know everthing. These are the great virtues of schdlarship, and they are particularly the virtues of science'.

Science has nothing to be ashamed of, not even in the ruins of Nagasaki'.

Science and aesthetics

That Science admits aesthetic criteria just like the arts, has been expressed by a number of great scientists and mathematicians. It has been said that science has something intrinsically poetic. Science has been considered to be a meeting place of two kinds of poetry; the poetry of action and the poetry of thought. According to Bohr, 'when it comes to atoms, language can be used only as in poetry. The poet, too, is not merely so concerned with describing facts as with creating images'.

When Einstein was reproached that his formula of gravitation was longer and more cumbersome than that of Newton, he apparently said that 'if one were to describe the truth, leave elegance to the tailor'. Yet, Einstein's equation has been considered by many to be complete and beautiful. According to Hardy, 'Beauty is the first test; there is no permanent place in the world for ugly mathematics'. The place of beauty in equations was expressed by Dirac many years ago. According to Dirac, 'it is more important to have beauty in one's equations than to have them fit experiment. If one is working from the point of view of getting beauty in one's equations, and if one has really a sound insight, one is on a sure line of progress. If there is not complete agreement between the results of one's work and experiment, one should not allow oneself to be too discouraged, because the discrepancy may well be due to minor features that are not properly taken into account and that will get cleared up with further developments of theory'. Dirac was a genius and I would not question his statements or convictions. I, however, find it difficult to accept what he said literally, although I appreciate the spirit of it.

The quest for beauty in science has found excellent expression in the writings of the astrophysicist, Chandrasekhar. While examining the question as to the extent to which the quest for beauty is an aim in the pursuit of science, Chandrasekhar quotes Poincare. 'The scientist does not study nature because it is useful to do so. He studies it because he takes pleasure in it; and he takes pleasure in it because it is beautiful. If nature were not beautiful, it would not be worth knowing and life would not be worth living ... I mean the intimate beauty which comes from the harmonious order of its parts and which a pure intelligence can grasp.... It is because simplicity and vastness are both beautiful that we seek by preference simple facts and vast facts; that we take delight, now in following the giant courses of the stars, now in scrutinizing with a microscope that prodigious smallness which is also a vastness, and, now in seeking in geological ages the traces of the past that attracts us because of its remoteness'. Commenting on Poincare's perception, Sullivan states that 'it is in the aesthetic value that the justification of the scientific theory is to be found and with it the justification of the scientific method.... The measure in which science falls short of art is the measure in which it is incomplete as science'.

Chandrasekhar adopts two criteria for beauty. The first is the criterion of Francis Bacon that 'there is no excellent beauty that hath not some strangeness in the proportion'. The second one, due to Heisenberg, states that 'Beauty is the proper conformity of the parts to one another and to the whole'. Clearly, as Chandrasekhar says, each of us, in our own modest ways, can achieve satisfaction in our quest for beauty in science.

I must express some misgivings about taking arguments based on beauty or such other aesthetic factors much too seriously since they may not be conducive to vigorous research demanded today. After all, we are no longer in the golden age when one was mainly concerned about universal physical laws for all time. Furthermore, to limit beauty to mathematical equations alone would be unfair to science. There is

beauty in the architecture of molecules and materials as well as in the pathways of transformations. There is also beauty in a properly designed and well-executed experiments. There is beauty even in the way science works and develops. 'It is the great beauty of our science that advancement in it, whether in a degree great or small, instead of exhausting the subject of research, opens the doors to further and more abundant knowledge, overflowing with beauty and utility', as stated by Faraday.

Science and utility

Science has its uses, but the basic urge to do science is not for utilitarian purposes. It was the view of Helmoltz that 'whosoever, in the pursuit of science seeks after immediate practical utility, be rest assured that he seeks in vain'. There is some truth in it because while pursuing science it would be difficult to fully imagine or to expect the full implications or usefulness of the results, although significant spin-offs may indeed result later. Mathematician Hardy, talking about his work, stated that 'I have never done anything useful, no discovery of mine has made, or is likely to make directly or indirectly, for good or ill, the least difference to the amenity of the world. Judged by all practical standards, the value of my mathematical life is nil; and outside mathematics, it is trivial anyhow. I have just one chance of escaping a verdict of complete triviality, that I may be judged to have created something is undeniable; the question is about its value'.

Although science is pursued by all good scientists without any expectations, we cannot forget the immense benefits that we have obtained through science. It is said that when Gladstone, the Chancellor of the Exchequer, asked Faraday about the practical worth of electricity, Faraday seems to have replied, 'One day, Sir, you may tax it'. As scientists, we should take care not to undermine the so-called applied science. Applied science can be as challenging as pure science and, what is more, it is somewhat more difficult. Scientists indulging in fundamental research tend to have a poor opinion of those who do applied science and this attitude has not helped anybody. Science requires many types of workers. To quote Peter Medawar, 'Among scientists are collectors, classifiers and compulsive tidiers-up; many are detectives by temperament and many are explorers; some are artists and others are artisans. There are poet-scientists and philosopher-scientists and even a few mystics'. But one of the main features that characterizes modern scientific research is that 'it is the art of the soluble', unlike politics which is the 'art of the possible'. 'Both are immensely practical-minded affairs. Good scientists study the most important problems they think they can solve'. And to solve real problems of mankind, 'we need to do science and more science' as Raman said. Nehru had the firm belief that 'it is science alone that can solve the problems of hunger and poverty, insanitation and illiteracy, of superstition and deadening custom and tradition, of vast resources running to waste, of a rich country inhabited by starving people.... The future belongs to science and to those who make friends with science'.

Science has been a great instrument of social change, all the greater because its object is not change but knowledge. Its silent appropriation of this important function, amid the din of political and religious strife, is the most vital of all the revolutions associated with the development of modern civilization.

Support for science

Although the tendency in the advanced countries is to support science through sources other than those of Government, there has been no doubt that even in these countries state intervention has been essential to ensure continued, balanced support and to accrue the benefits of the results of scientific work for national development. In countries like India, there is no source other than the Government for the support of science. Unfortunately, what has happened is that there is little appreciation in many quarters regarding the responsibility of the Government in actually ensuring that science is well supported and that the state of health of science is satisfactory. This is because not only some of the ministers, planners and administrators at the highest level are ignorant of science but the same defect runs through almost all the departments of the civil service. It is said to be nearly universal in the House of Commons in Britain, and is shared by the general public, including a large proportion of those engaged in industrial and commercial enterprise. This ignorance is affecting science badly, especially in countries such as India. I am reminded of the story narrated by Al-Biruni. Once a sage was asked why scholars and scientists always flocked to the doors of the rich, while the rich are not inclined to call at the doors of the scientists. The sage answered, 'The scholars are well aware of the use of money but the rich are ignorant of the nobility of science'.

Frederick Dainton wrote sometime ago, 'Accountants and second rate business school jargon are in the ascendent. Costs, which rise rapidly, and are easily ascertained and comprehensible, now weigh more heavily in the scales than the unquantifiable and unpredictable values, and future material progress. Perhaps, science will only regain its lost primacy as people and Government begin to recognise that sound scientific work is the only secure basis for the

construction of policies and to ensure the survival of Mankind without irreversible damage to Planet Earth'. I feel that the attitude of many politicians, planners and administrators has not altogether been healthy and has not been based on sound judgement. I recall the statement made by John Kenneth Galbraith regarding Mrs Thatcher's policies in Britain. ' She is the reflection of comfortable middle class values that do not take seriously the continuing unemployment. What I particularly regret is that she does not take seriously, the intellectual decline. Having given up the empire and the mass production of industrial goods, Britain's future lay in its scientific and artistic pre-eminence. Mrs Thatcher will long be remembered for the damage she has done'. I believe that there is a lesson in this statement.

Experimental science

I am a physical scientist. In particular, I am a physical chemist or a chemical physicist doing experiments. I believe that doing experiments is the main purpose of science. In science we have theories and models. As Kapitza said, 'theory is a good thing, but a good experiment lasts for ever'. Leonardo da Vinci seems to have said that 'there is no higher or lower knowledge but only one flowing out of experimentation'. According to Eigen, 'A theory has only the alternative of being right or wrong; a model has a third possibility. It may be right but irrelevant'. Theoretical research without relation to experiment tends to become sterile. I like what Faraday said about experiments. 'Nothing is too wonderful to be true if it be consistent with the laws of Nature and in such things as these, experiment is the best test of such consistency.' Michael Faraday was an experimentalist par excellence and probably the greatest experimentalist of all time.

While it is pointless to discuss the relative importance of experimental and theoretical research, there seems little doubt that when experimental research dies, science also dies in that country. This should be a matter of serious concern to us, since there are very few people doing good experimental work in India, at least in physical sciences and related areas.

Reflections

Science is an essential part of my life. Without science I am unable to live. When I started working in science four decades ago, I did not know that this would happen. I took up science as a profession and as I gradually went on working, I got addicted to it. Soon I found that science was not only running my life but was dictating its terms. There was no way I could plan my life without science. Every aspect of my living is linked to what I do in my laboratory. If my work in the laboratory gets affected by what I do in other spheres of life, then I stop indulging in those activities. I have found that doing science alone is not as interesting as doing science with young people. Being a teacher has therefore been extremely important to me. Being a teacher alone without doing research has no meaning, either. Kalidasa wrote many centuries ago:

> If a professor thinks what matters most,
> is to have gained an academic post,
> where he can earn a livelihood, and then
> neglect research, let controversy rest,
> he is but a petty tradesman at the best,
> selling retail the work of other men.

Those of us who pursue science by working with young people cannot forget our prime responsibility in bringing new generations of scientists. We have to give everything we have to the young and guide them in a manner that they are able to blossom as scientists, fully exploiting their native capabilities. It is difficult to convey the excitement in science unless one has experienced it, 'the dramatic feeling of sudden enlightenment that floods the mind when the right idea finally clinches into space'. Yet, by the way one lives and by the way one works, it is possible that one may be able to communicate the right message to the young. I have found that my Indian background is specially helpful in developing a less selfish and a more purposeful approach to living.

A great diversion to many a good scientist has been to get involved in administration. Unfortunately, it is also a necessary and unavoidable evil. I realize that one cannot possibly be like Michael Faraday. Faraday, when approached to take the Presidentship of the Royal Society, apparently said, 'I must remain plain Michael Faraday to the last; and let me now tell you that if I accepted the honour which the Royal Society desires to confer upon me, I would not answer for the integrity of my intellect for a single year'. This is too much to ask of ordinary mortals like myself, yet there is no doubt that those of us who have done even a little bit of administration have lost valuable time for research and those of us who do research beyond all other commitments, often find that we occasionally miss something crucial and important because of our pre-occupation with administration. Administrative chores and worries frequently come in the way of the crucial minutes of unperturbed meditation. I sincerely advise all those aspiring young scientists who really want to make a mark in science, never to touch any form of administration unless it is just to govern a small research group.

Many scientists worry about status. I have heard people say that an Inspector of Police in the locality

has greater respect of the community than a scientist. I do not know what kind of respect they have in mind. I believe that this is not the kind of thing one should worry about. Intellectuals, who own and create knowledge, are the most important component of society and this determines their status and nothing else. We cannot possibly compare the status of a good scientist with that of an Inspector of Police or an administrator in Government. I think that a good scientist does get respect where he belongs, by the international and national scientific community. I also feel that salary and status are irrelevant parameters in science; I have always felt that I have been an overpaid research scholar doing what I like most. It so happens that scientists themselves treat administrators with undue respect and prefer politicians to inaugurate symposia. It is necessary for us to have a good sense of humour. Some of us suffer from a persecution complex, possibly with justification. A man does not attain the status of Galileo because he is persecuted. He must also be a good scientist.

Some scientists are conservative about publishing while others are prolific. While there is no simple rule about how much to publish or not to publish, there is no denying the fact that, as Benjamin Franklin as well as Faraday put it, the main activity of scientists is to 'work, finish and publish'. I am not ashamed of publishing. I have known great scientists who have published several hundred papers. Both Faraday and Raman published over 450 papers. I have also known extraordinary men who have published very few papers. I have known theoreticians, like Nevill Mott, who have published consistently and constantly for several decades. The real problem with us in India, however, is that a large number of us publish a large number of papers which are irrelevant. There are very few good papers coming from India especially in experimental physical sciences, and this is harmful. A small number of good papers coming from a large country like India has little visibility.

Research facilities are poor in most institutions in India. Blackett was of the view that 'A first rate laboratory is one where even mediocre scientists produce outstanding work'. This is probably what happens when some of us go to advanced countries. We must have at least some good laboratories where we can perform and where most of us can do our best to produce results that are worthwhile. While facilities and support are declining, science itself is galloping. The pace at which science is moving is so great indeed that the frontiers of today often become the centres tomorrow and this happens all the time. The present-day rate of progress in science allows no respite and in most areas competition is intense. To be counted, one has to fearlessly take up difficult, contemporary problems. Safe problems are easier to work on, but get little notice.

In spite of the many limitations and difficulties, there are still some of us who want to do science. It is useful, therefore, to recall the lives and work of great men who accomplished much against all odds and would not give up easily. We should not be unnecessarily worried about public opinion. After all, public opinion is not discriminating and is likely to interpret the demand of scientists as meaning that science can be had for money. But science is not for sale.

Freedom may be the first born daughter of science. Unfortunately, however, science seems to have lost her freedom in recent years. 'It has become a productive force' as Kapitza said. 'It has even become rich but it has become enslaved' I am not sure whether men like Faraday, Rutherford and Raman would be happy to do science under the present circumstances.

Samuel Coleridge wrote long ago, 'the first man of science was he who looked into the thing, not to learn whether it furnished him with food, or shelter, or weapons, or tools, or armaments or playwiths but who sought to know it for the gratification of knowing'. I believe that this spirit is still prevalent amongst some of us. Raman said that 'the pursuit of science derives its motive power from what is essentially a creative urge. The painter, the sculptor, the architect and the poet, each in his own way, derives his inspiration from Nature and seeks to represent her through his chosen medium.... The man of science, like the exponents of art, subjects himself to a rigorous discipline,... Science is a fusion of man's aesthetic and intellectual functions devoted to the representation of Nature'.

I have always felt a sense of admiration and awe by the way Ramanujan worked. He had no need of university education. With all his problems, he went on doing mathematics, writing page after page of equations in his notebooks. What was the urge that made him do that? It was not money. His health was terrible. He had no real patrons until he proved himself and even those patrons probably learnt more from him than he from them. How could he do so much in such a short life amidst suffering and sacrifice?

One cannot help but marvel at the way Michael Faraday carried out experiments. Faraday who hardly had any formal education was a genius propelled by an urge to explore. He was painstaking and dedicated and was a storehouse of intellectual energy. He just would not stop. If one were to look at Faraday's contributions by today's standards, he could have easily received five or six Nobel prizes. No one really guided him or motivated him. It was purely the case of the inner urge inspiring him to carry out experiment after experiment. In the year 1933 alone, Faraday made seven or eight major discoveries. Interestingly, he recorded an important discovery on 24 December and

another on 26 December; there is no record for 25 December since it was Christmas Day.

I have been equally baffled by the artistic productivity of Michael Angelo who took five years or more to produce his masterpieces on the extensive ceiling of the Sistine chapel. He painted alone without assistance, day and night. He used to paint hours on end, often in the dark with a candle on his forehead and another on his shoulder, with his head bent backwards to face the ceiling. At the completion of this monumental work, he was temporarily deformed and could not bend his neck. He could not walk because his toe nails had overgrown in the shoes which he had not removed in years.

In my years of working as a scientist, I have found science to be a demanding master, not easy to satisfy. Only those who completely submit to it seem to reap the benefits in terms of intellectual excitement and satisfaction. Those who treat science as a pastime or a hobby, may get little rewards, but nothing else. For a real scientist, all days are working days. For someone mentally absorbed in his work, there are no working hours. Wherever one is, and whatever one is doing, one is always under the effect of the undercurrent of one's scientific pursuits, consciously or unconsciously. When such a thing happens, the need for an external stimulus to pursue science disappears. It is only then that anxiety about recognition and rewards also disappears. This mental state is necessary for philosophically well-adjusted living. The effort to attain this state is difficult and may demand considerable personal sacrifice, often in terms of social life; then, it is worth it.

What is also wonderful is that there is no limit to scientific pursuits. This limitless world scientists belong to, makes life worth living and more challenging. I have always been and continue to be thrilled by the way research areas develop as one pursues ideas. 'Great Oaks from little acorns.' As Herbert Brown has written, 'What starts off as a mere grain of pollen, develops into an acorn. The acorn then grows into an Oak tree. The Oak tree develops into a forest. We then begin to see the outlines of a whole new continent'. There are undoubtedly many such continents lying undiscovered around us. Much of the life of scientists is spent in search of the grain of pollen or working in a forest. Happy are those who witness the growth of a pollen grain into a continent. This can happen by chance, but chance only favours the prepared mind; it happens mainly due to persistent effort. I have been making all effort possible in the last four decades to seek happiness through scientific explorations, and more so, by keeping company of those who are similarly occupied. The main thing that has happened is that doing science has become a way of life. I am indeed grateful for this blessing.

Star clusters in the Magellanic Clouds and their mass functions

Ram Sagar

Study of star clusters in a galaxy throws light not only on the processes of star formation and evolution in the galaxy but also on the structure and evolution of the galaxy. In this respect, star clusters of the Magellanic Clouds are of extreme importance because they differ from those of our galaxy in many important respects, e.g. they occupy regions of the age and metallicity domain which are not populated in our galaxy. Therefore they extend the range of comparison between stellar evolutionary theory and observational data. As the evolutionary history of the Magellanic Clouds has been very different from that of our galaxy, study of the mass function of those young star clusters which are rich in stars, and span a wide mass range, can provide the answer to the astrophysically important question of the universality of the shape of the initial mass function in time and space.

A star cluster is a group of dynamically associated stars, presumably created from the same material at about the same time and, consequently, located at the same distance. All the cluster members move together through the star fields of its galaxy and will maintain their identity for some time which is known as the cluster lifetime. A colour photograph of the southern

Ram Sagar is in the Indian Institute of Astrophysics, Bangalore 560 034, India