C. N. R. Rao

A. K. Ganguli and T. V. Ramakrishnan

Bharat Ratna Professor Chintamani Nagesa Ramachandra Rao (C. N. R. Rao), now in his 83rd year, a passionate and dedicated scientist, is a multi-faceted living legend. He is the only living Indian scientist who is a Bharat Ratna (gem of India), the country's highest civilian honour. It was awarded to him for his lifelong commitment to high quality science, his exemplary achievement, and his leadership over decades. Rao ranks easily as one of the most prominent chemists of the world. Typically, a living legend in the academic world is a figure who inspires students and colleagues with his insights, attitudes and work. He is that and much more. He is also an unparalleled leader and mover in Indian science over the last many decades, a farsighted and watchful sentinel for science in India and elsewhere, a great builder of institutions, and a joyous communicator of science to thousands of young people. We try to present here a partial picture of this many-dimensional giant. We include, as examples, excerpts from his direct writings and speeches about science and Indian science. We situate this in the context of his life journey[1].

Lifeline, personal and professional

Rao was born in Bangalore to Hanumanth Nagesa Rao and Nagamma. He was the only child; his learned parents created an academic environment for him. From his mother, the most influential person in his childhood, he imbibed his strong background in traditional Hindu literature and from his father, an English background. His father, an inspector of schools, enrolled him in a Kannada medium, nationalist oriented school, the Acharya Pathashala, in Basavanagudi. This was a life-forming cultural experience; it also had a lasting influence on his interest in chemistry.

A precocious student, Rao entered Central College, Bangalore at the age of fifteen and obtained B Sc in 1951. A bold decision led him to Banaras Hindu University, from where he obtained M Sc in 1953, and where he encountered Pauling's work on chemical bonds[2]. Experiencing the life of research, he was permanently hooked to it as a chemist. Varanasi transformed his life; he could also listen to Pt Omkarnath Thakur and get close to the idol at the Vishwanath Temple. Rao, who started his work for Ph D at IIT Kharagpur, went to Purdue and completed his Ph D there in less than three years in Chemical Physics, and after postdoctoral work at the University of California, Berkeley, joined the Indian Institute of Science (IISc), Bangalore as a young faculty member. The premier institute had no facilities; as he says 'you would get string and sealing wax and that's about it'. It says something for his indomitable drive that one of his long-lasting contributions, to the rutile-anatase transition in TiO_2 dates from this period. Two of his books translated into several languages, on ultraviolet and visible spectroscopy, as well as on infrared spectroscopy are from this stay. He also recognized solid state chemistry/materials chemistry as a potentially rich field and eventually became one of the pioneering figures, a world leader, in it.

After four years in IISc, Rao, not yet thirty, joined the very new IIT Kanpur in 1963. His research and academic leadership made the department the most exciting place for chemistry in India. Many of the young faculty members from there rose to national and international eminence. It continues to be a remarkable centre for chemical education and research. In spite of difficulties which would have diverted or discouraged almost all of us, Rao's legendary qualities began to be evident. The work by him and his group on uniquely broad themes in physical chemistry and material chemistry is pioneering. It transcended conventional disciplinary boundaries; one of us (TVR) remembers that his introduction to Anderson insulators and to Mott variable range hopping transport in disordered insulating materials occurred there. His pioneering work in solid state chemistry began to be recognized internationally; he was for example awarded the Marlow Medal of the Faraday Society, UK in 1967, and spent a year as Commonwealth Visiting Professor at Oxford. Nationally, academic recognition in the form of the Bhatnagar Award (1968) and the Fellowship of the Indian Academy of Sciences (1965, a personal choice of the great C. V. Raman) came to Rao when he was barely thirty. He was also becoming a national figure in science policy; he was the youngest member of the National Council for Science

C. N. R. Rao

Department of Chemistry, Banaras Hindu University, 1953

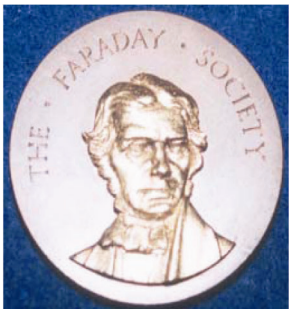
and Technology (NCST) which came into being in 1971 when C. Subramanian was the Minister of Science in Delhi.

Starting in 1974 in small temporary premises, the Solid State and Structural Chemistry Unit of the IISc, conceived and developed by Rao, has grown into one of the major world centres in the subject. This development is due to a number of factors. One is the wide variety of activities and interests which had some core directions such as transition metal oxides, electron spectroscopy, and electrochemistry and kept gathering new areas, e.g. manganites, fullerenes and nanotubes. Another is that both the level and amount of successful work were always very high. A third is the nurturing of a large number of students with skill, effort and care. Animating all this was the fertile and passionate scientific imagination of a high order, and an indomitable spirit which found a way around all obstacles.

During his tenure as Director of the Indian Institute of Science (1984–1994) he recruited a large number of faculty at all levels in all departments through sustained proactive efforts at attracting them. Massive support both for research and improving infrastructure, was sought and provided; the transformation of the IISc to a visibly premier higher education/research institution in India, and one of the leading ones in the world, was accomplished. The physical landscape and organization of IISc changed greatly. His efforts saw to the establishment of the Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) as a commemoration of Jawaharlal Nehru's birth centenary in 1989; he was its first President, a position he held till 1999. He continues to work there as Linus Pauling Professor, and National Research Professor. He founded the International Centre for Materials Science (ICMS) there in 2010.

Rao was Chair and a vigorous moving spirit of the Science Advisory Council to the Prime Minister from 2005 till 2014. His demanding and active leadership of India's nanoscience/nanotechnology programme in the last decade has seen the country become one of the top three in the world in this field. It is a part of Rao's continuing professional life.

Joined IIT Kanpur in 1963



Marlow medal by Faraday Society 1967

Awarded Bharat Ratna by Hon'ble 'President of India' (2014)

IISc, Bangalore

JNCASR, Bangalore

ICMS, Bangalore

Teacher and mentor

Rao feels that the most enjoyable aspect of his career has been working with young students. Over 150 students have received the Ph D degree working with him. Besides young co-workers and post-doctoral fellows, he collaborated widely with scientists in Europe and USA. A large number of students mentored and strongly influenced by him, have developed into accomplished scientists.

He has a lifelong interest in teaching and interacting with students at all stages of growth. In the IIT Kanpur years, he was a very active member of a small group of visionaries that developed a great undergraduate science–technology programme, for the first time in India, and now widely emulated. A major textbook on General Chemistry was developed there. In the last 10 to 15 years, Rao has been making sustained efforts to bring out science education materials for school children. Particularly noteworthy are his recent books titled *Learning Science*[3] and *Understanding Chemistry*. He

Rao with school children

has also produced multimedia packages on chemistry and general science for children, besides simple books with extensive illustrations. He regularly delivers lectures (with demonstrations in many cases) to children, hundreds of them, in various parts of the country. He replies to every letter addressed to him by students from schools and colleges.

One of the world's leading chemists

Rao is one of the world's pre-eminent chemists. He is one of the founders of Materials Chemistry. The subject did not exist as a discipline in the early 1950s when he started it with remarkable prescience. In his book *The Coming of Materials Science*, the author, Robert W. Cahn, an eminent metallurgist and materials scientist, says that Rao is one of the greatest modern exponents of materials chemistry. Because of the enormous and wide-ranging contributions of Rao and his group, this field is one of the most vital in chemistry. What is truly remarkable is the multidimensional nature of his research in this field which covers areas from hydrogen bonding to metal insulator transition in solids, spectroscopy, surface chemistry, framework solids, novel superconductors, fullerenes, carbon nanotubes, colossal magnetoresistance compounds, graphene[4], nanowires[5], water splitting and many more.

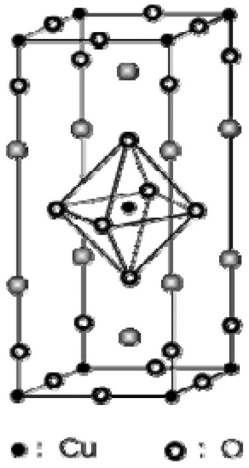
A number of qualitatively new departures are associated with him. For example, he was the first[6] to realize in 1984 or so that the insulating, antiferromagnetic cuprates (La_2CuO_4) are nearly two-dimensional layered compounds and are strong correlation-driven Mott insulators. (His work on such cuprates actually started in the early seventies[7].) When the cuprates were seen to be home to high temperature superconductivity[8–10] (a major revolution in science which occurred around 1987) he independently synthesized the 123 cuprate, the first liquid nitrogen temperature superconductor. He also discovered a host of other series of superconductors. The first synthesis and characterization of the unusual Y junction carbon nanotubes was accomplished in his laboratory in the mid-1990s. A large number of processes and materials, now staple in the field, owe their origin to Rao.

Out of the extensive contributions of Rao and his group (detailed in more than 1500 papers!) we mention here just a miniscule fraction. For example, he contributed extensively in the nineties to our knowledge of transition metal oxides such as $Ln_{1-x}A_xMnO_3$, the so-called colossal magnetoresistence manganites, making new materials in the family and investigating spin, orbital and magnetic ordering in these materials[11]. He and his co-workers were among the first to discuss phase separation in these manganites[12]. He discovered new multiferroic materials (which are simultaneously magnetic and ferroelectric)[13]. In another area, that of open framework systems, he has shown how the formation of complex three-dimensional architectures involves a progressive building up from zero or one-dimensional structures to higher dimensions (such as the sodalite structure), the spontaneous self-assembly of a precursor state being an important step. He has also shown how the mechanical properties of related metal organic framework (MOF) structures can be improved by incorporating nanosheets of boron nitride (BN)[14,15].

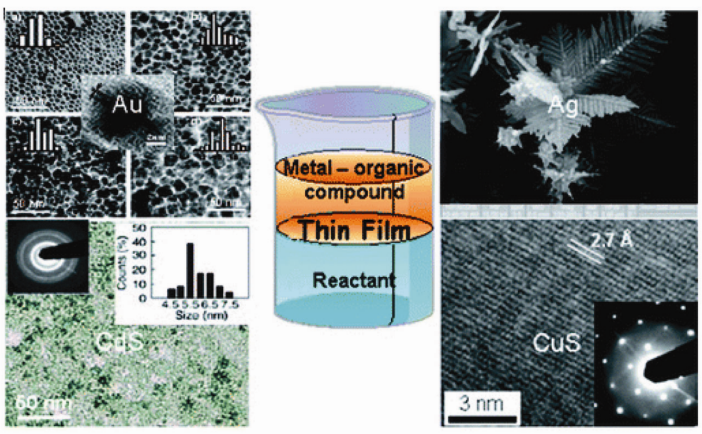
The area of carbon-based research has occupied Rao's interest from the 1990s with fullerenes as a beginning. Carbon nanotubes, novel junctions of these, graphene, new routes for making these nanosystems, chemically modifying them in interesting ways, physically similar alternatives to these systems, are some examples. In all of these, his amazing chemical insight and his passion for discovery have found expression.

Rao has been interested for long in chemically engineering inorganic materials to provide desirable physical properties. For example, he succeeded, using a soft chemistry route, in making good quality nanocrystals of GaN and other nitrides showing quantum confinement[16]. In the last few years, he has shown how aleovalent substitution in many binary A_NB_{B-N} semiconductors can be used to tailor physical properties such as bandgap[17]. This has clear implications for efficient solar energy photovaltaics.

One of the characteristics of Rao's materials chemistry work is that many of the breakthroughs could have led to major applications if pursued in depth and detail. This has not happened in India. Internationally, he is regarded as 'one of the world's foremost solid state and materials chemists'. This is the first sentence in citation of the Dan David Prize awarded to him in 2005. (The Dan David Prize is a highly prestigious international award originating from Israel. It is given annually in three areas, past, present and future. Materials science was chosen in



La_2CuO_4



Nanomaterials synthesized by Rao's group

2005 for the last category, and the two co-winners were George Whitesides of Harvard and Robert Langer of MIT.) Further a field, his professional stature is indicated by the following, for example. The Institute of Physics, UK elected him (a chemist) and the legendary physicist and Nobelist V. M. Ginzburg to its Honorary Fellowship in 2006. As early as 1976, he was elected Centennial Foreign Fellow of the American Chemical Society. He was the representative of the *entire* Fellowship of nearly 1500 UK, Commonwealth and world scientists at the 350th anniversary meeting of the Royal Society, London, in 2010. He is one of the only dozen or so foreign members of the Japan Academy.

Institution builder

Rao is not only an inspirational researcher and educator. He is a unique builder of scientific institutions in India. It started with the Department of Chemistry, IIT Kanpur in the sixties. He helped build up this department, and imparted (mainly through example) an ethos which saw its preeminence in the ensuing decades. The institution could be the Solid State and Structural Chemistry Unit of the IISc Bangalore, a relatively small professional group which was created and nurtured by him since the mid-1970s. It could be an already existing great institution like IISc, Bangalore of which he was the transformative Director for a decade (1984–94). It could be the Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) in Jakkur, Bangalore, which originates from his advocacy in 1989 and has grown under his direction and inspiration into a remarkable, highly productive, wide ranging science and technology research centre. More recently, about a decade ago during his stewardship of the SAC to PM, a group of five IISERs (Indian Institute of Science Education and Research) were set up in Kolkata, Pune, Bhopal, Thiruvananthapuram and Mohali. This was largely due to his leadership and involvement. The quality of these institutions and the consistent high level of support have already made a major contribution to quality undergraduate science education in an active research ambience. Their success can be gauged from the fact that several new IISERs (at Bhubaneswar and Tirupati) have been sought for and have come into existence.

Science leader

Rao has been and is an active leader in the development of high quality science. His care and concern, his catholic interests, his pragmatism and drive added to his stature, and amazing breadth as well as depth of knowledge of science and of scientists, make him a singular leader, one who is a lifelong working scientist and has never been a science administrator in Delhi. He is always proactive and a genuine, path making, leader.

As mentioned earlier, in the seventies, Rao was the youngest member of the first national group on science and technology, formed by the then Minister of Science, C. Subramanian, another Bharat Ratna. He has been the Chairman of the Science Advisory Council to two Prime Ministers, Rajiv Gandhi and Manmohan Singh. His activities and advice are now woven into the warp and woof of Indian science. He founded and was the moving spirit behind two major research bodies, the Chemical Research Society of India and the Materials Research Society of India. For decades, he has been the face of science in an unbelievable number of activities ranging from academic review of institutions, to Governing Councils and to the choice of science administrators at the highest levels.

Internationally, Rao's leadership is visible in several ways. A few examples are the following. As President of the IUPAC (International Union of Pure and Applied Chemistry) during 1985–1987, he played a key role in the restructuring of the organization such that it reflected modern trends in chemistry. As the President of the Third World Academy of Sciences (the first after the demise of the founder and Nobel Prize winner Abdus Salam) he gave it, at a critical phase in its life, several new directions. Appreciation for world class science in the Third World and focus on scientific growth in the least developed countries (LDCs) are two of them.

Rao's leadership in science at a professional level, away from the public gaze, is no less significant. He is on the Editorial Board of a number of significant international journals. Through a choice of subject direction and through his own contributory articles, he is an immensely powerful influence on solid state chemistry, materials chemistry and nanoscience. He has been a reviewer and adviser at a professional level, to departments of chemistry internationally; many governments have sought his advice for restructuring and reinvigorating science activities in their countries.

Baldev Raj, currently director of the National Institute of Advanced Studies, Bangalore, has described CNR 'as a colossal teacher and scientist with contributions in solid state chemistry and materials research which have impacted the chosen domains of his pursuits namely spectroscopy, nanomaterials, multiferroics, high temperature superconductivity, etc. in a substantial way. He is unique in his successes and perspectives right from an early age. His abilities are demonstrated by his successes, as a child to studies, scientific works, publications and distinctions. Each period of his life has been brighter and more meaningful as compared to previous one; characteristic of a true scientist.'

Science in India, science…

We feel that Rao's concern, involvement and attitudes regarding the above, which are a part of his legendary persona, come through best in his own words. We therefore include here extracts from his many forthright and heartfelt statements on it, made in speeches, writings, interviews, TV programmes, etc.

Rao says that 'It is not true that Indian science in general is doing badly. Today some institutions have facilities as good as any university in the world but it did take us a long time to get here. In India, wherever we have had targeted funding we have done well. For instance, in the last 10 years, every institution has worked in nano science and now India is now number three in the world in this area of research. This gives us an important lesson. We should do the same in key areas like energy and healthcare. There are lots of scientific issues that India has cause for concern. We need about 400,000 MW of electricity in the next 20 years and the question arises: where do we get this from? So we have to start finding alternative sources of energy. The overall quality of science in India is still not up to the mark. Firstly, this is because universities are not

funded well. Our universities are in a very poor state. Everybody wants to get admission in one of the IITs but that's not possible. However, if we had 50 other such institutions we could have bright Indians working there and the quality of research will go up immediately. Secondly, we have to be able to pick the right area of research and invest in it. Young students often lack good institutions where they can further their research. Most students today also seem to feel that careers like business and banking are more financially rewarding. But now the salary for scientists is equally good. In fact, India is now ranked number three for salary satisfaction for scientists. Most fresh Assistant Professors get about a lakh per month which is pretty good. My first salary was Rs 720. Income should not be an issue today. Society also plays a very important role in the progress of science. It seems students who pursue B Sc are made fun of saying they are not good in studies. The mindset is such that if you are an engineering student in even a second rate institute then you are thought to be better. It is only in the last 10 to 15 years that we are able to receive much more (relatively) support for science. Investment in science has been very poor in the country. However, for the amount of investment that has been made we have done reasonably well. We made great contribution to atomic energy and space technology and we have world renowned institutions like the IITs.'

He adds 'Scientific research has progressed in India in the sense that there are more scientists today. The quantity of science that India contributes to the world has roughly remained the same for the last few decades (~3% of world science). China's contribution has increased to 15%. The quality of research has also not improved as a whole (contribution of less than 1% to top level research in the world) although there are individuals who have done well. In all the enthusiasm of using bright students to sell soaps and credit cards, this is where we have landed. Plus there is too much of emphasis on IT. Look at Bombay University or Madras University. I do not know even one good scientist working in these places which produced luminaries at one time. My only hope and prayer is that India becomes a great scientific power. If that has to happen, the quality and quantity of scientific research have to both increase substantially. We have to invest more in science. We have to build more and better institutions. We have to encourage individuals. At least 2% of the GDP should go for science. Today, much of scientific investment goes to agencies such as atomic energy, space etc. and not to what I call small scale research (carried out by individuals in little laboratories) which is truly responsible for progress in science. We scientists have also to work much harder and take up really important problems. As Faraday said, it is the choice of the problem that is difficult and not doing it.'

On his philosophy of research he says: 'Of all the statements in science, one statement that I have always liked is from Faraday: Science is nothing but work, finish and publish. Another is G. N. Lewis's statement: Physical chemistry is anything that is interesting. Pauling said: To have a great idea you need to have many good ideas. I have been productive and publishing throughout my career. I have published at least 25–30 research papers every year but the quality of research and also my effort in research have improved after my 60th year. It became better after my 70th year and I have been cited much more after my 70th year.'

In terms of areas of research he says: 'IITs should spend more effort on research and innovation if they are to be like MIT. Professors should not only do outstanding teaching but also do outstanding research. They should also own start-up companies. There is much that IITs can do, and they should not become glorified engineering colleges. It is also true that we have not provided as much funding and other types of support that IITs require. We should help them in many ways and not start too many IITs without planning. We should ensure not to destroy the IIT brand.'

Rao deeply feels for Indian science[18] and stresses the point that in science we have to pick out the best areas for investment. He says: 'Wherever we have done that we have succeeded'. In a letter to a dear friend he wrote in 2012–13 he shares his anguish 'what concerns me more is the situation with respect to science. I have noticed mild indifference in the scientific community with regard to our performance and the status of science in the country. While I am not worried that India is not publishing as much as China, I do worry about the quality of work that we produce, the absence of a critical mass of good scientists in a given area, and the moderate impact of our science on society and on science itself. If we have to do well in science, we have to change not only the kind of science we do but also our attitudes. Many of us become extremely critical of others and some of us do moral policing. It will be much better that we stick to science and do something worthwhile rather than look for faults in others. I do hope that pulling down institutions and colleagues does not become a pastime.'

Rao strongly believes that teachers are responsible for the future of India and that is why he has been pleading with the government to have special agenda for teachers in the next 5 years and the Planning Commission has agreed to it. He adds that he himself comes from a family of teachers and has a great love for this profession. India can never become a military power or even an economic power. But there is enormous potential for it to become a knowledge power.

CNR Rao the person

Science is done by human beings. The kind of person a scientist is, makes a great difference. Rao's nature as a human being contributes greatly to his legendary qualities as a scientist, as we hope to briefly indicate now.

Rao has a unique ability to comprehend difficult issues in a very short time. He can measure precisely the capability of a person in almost any discipline. Hence, during discussions with scientists, specially young faculty, he could spot brilliance and also give them suggestions and directions, which would take their career towards greater heights over a period of time. He would engage himself in discussions during breaks in any meeting or conference to talk especially with students and young faculty. This trait of mentoring brings the entire scientific youth close to Rao. He would also be very upfront about his reservations if any on the kind of choice of problems and related scientific activities and convey his views directly to 'people' concerned.

Rao says: 'I feel that the absence of generosity and good nature will hurt us in science more than any other factor. Generosity is essential for science to thrive. While it may be true that many of our institutions are not doing well as they

should be doing, it is also true that a negative atmosphere further hampers progress. Even in well-established and prosperous institutions in the country, I sense an unexplained feeling of dissatisfaction. I have not found this in China, and the Chinese are very nationalistic.'

One of his great qualities is that he takes personal interest in the well-being of anybody who comes across his life even for a small period of time. It may be a gardener, his driver, students, young faculty, senior colleagues, other administrators…. anyone who was in need of some direction or help, Rao always came forward. This included giving monetary help, advice for the best doctor, best school, area of research… he has the knowledge of the best thing available in the world in any area and will go out of the way to help people trying to get professional help of the highest order.

Overall, Rao has a very unique personality with universal appeal. His generosity, encouraging attitude and feeling for colleagues, students and people working around him is felt by one and all. He has helped many achieve their dreams and has encouraged every 'hard-working person' attain his height of success, glory and fame. He also has the great quality of forgiving very soon.

When we asked him, from where he derives his strength, Rao says 'The main strength in my life has been the great faith in learning as a way to live one's life. One should do everything possible to attain the highest level of intellectual accomplishment in any given endeavour and this faith has helped me not to give up.'

On being asked what he would like to say to young children, students of science, young scientists and scientific administrators, he says: 'I have the following to say to young children. Children of tomorrow will face a crowded India, but they should also realize that there will be many opportunities. Some of the opportunities will have to be created by them. For this reason, they have to be alert, attentive and always keep their antennas working. At the same time, they should make up their mind on what they would like to do and not give up that mission. Pick up whatever area you are interested in (preferably a lonely road where you can shine) and then don't give up. It is doggedness and hard work that are most important for success.'

For young scientists, 'We should love to learn, and to create something new. Success comes only when there is dedication, tenacity and hard work.'

For Scientific Administrators, 'The only suggestion I have is that they should not forget that they are scientists and not become babus. They should do everything possible to promote science and not become too rules-minded.'

On being asked if he has any regrets in his life, which he would like to change if given a chance, Rao says that 'I have no regrets in my life. I consider myself to be one of the happiest men in the world doing what I like most. If I were to be born again, I will do exactly what I have done. Right now, if you were to ask me what I would like to do, I don't mind going back to my Ph D days.'

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A. K. GANGULI[1,2]
T. V. RAMAKRISHNAN[3]

[1]*Institute of Nano Science and Technology, Sector-64, Mohali 160 062, India*
[2]*Department of Chemistry, Indian Institute of Technology, New Delhi 110 016, India*
e-mail: ashok@chemistry.iitd.ac.in
[3]*Department of Physics, Banaras Hindu University, Varanasi 221 005, India*
e-mail: tvrama@bhu.ac.in