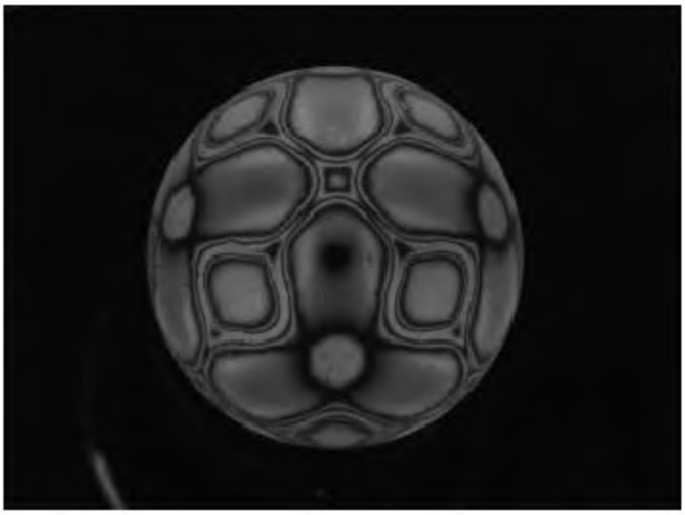
The Coming of Materials Science. Robert W. Cahn (Series ed.), Pergamon Materials Series, Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlingtox, Oxford OX5 1GB, UK. 2001. 568 pp. Price: US$ 64.00.

The Coming of Materials Science marks another virtuoso performance by R. W. Cahn, the famous author (or editor) of such prodigious publications as *Materials Science and Technology*: *A Comprehensive Treatment* running into 25 books (1991–2000), *Artifice and Artifacts: 100 Essays on Materials Science* (1992), *Concise Encyclopedia of Materials Characterisation* (1993) and *Physical Metallurgy* in 3 volumes (1996). Apart from possessing innate, extraordinary skills as a powerful writer, Cahn is a discoverer himself. The earliest experimental evidence for the existence of dislocations was provided by him in 1947 in his observation of polygonization in a deformed and lightly annealed metal crystal. This important discovery places Cahn among the league of pioneers in physical metallurgy. Moreover, he has hovered, for over several decades, around the centre stage of important scientific findings which have together developed into what we now designate and accept as materials science. Clearly, the field of materials science could not have boasted of an abler chronicler to document the history of materials science.

The Coming of Materials Science, which runs into 15 chapters, is a particularly readable record of the origins of the discipline in the early 1950s in USA, its slow evolution through a process of melding topics in physical chemistry, solid state physics, physical metallurgy, and more recently even in apparently far-removed biology. The book seeks to demonstrate the emergence of materials science by this process of integration and then its establishment in its own right as a new and a 'real' discipline. At a time when interdisciplinarity in its metamorphosed expression, borderless science, is gaining prominence as an inevitable approach to new knowledge, Cahn's pioneering account of the emergence of a new discipline has a marvellous topic to deal with, for materials science is itself a subject of *in situ* interdisciplinarity. The remarkable success of Cahn's present monumental task is bound to spur similar compilations in other fields of enquiry.

This treatise is not limited to tracing the seeds of discoveries and their subsequent nurturing. Contained here are also descriptions of the birth and growth of journals, prominent journals in chemistry, for instance starting with the *Journal of American Chemical Society*, which recently celebrated its 125th year of publication, *Zeitschrift für Physikalische Chemie* (1887), *Journal of Physical Chemistry* (1896), *Journal of Chemical Physics* (1933), *Journal of Physical Chemistry Chemical Physics* (1999). According to Cahn, *PCCP* was a venture of the European Chemical Societies, born out of a revolt against the constraining disciplinary structure of a physical science. Naturally following are similar descriptions of periodicals in physical metallurgy and materials science, including many specialist journals in related topics. Cahn himself had a pioneering role in three now well-established journals: *Journal of Nuclear Materials* (1959), *Journal of Materials Research* (1985), and *Journal of Materials Science* (1966), the first broad-spectrum journal in materials science.


Highly polished spherical copper monocrystal, oxidized to show anisotropy of oxidation rates (after Young, F. W. Jr., Cathcart, J. V. and Gwathmey, A. F., *Acta Metallurgica*, 1956, **4**, 145.)

Also included in the volume is a history of professional bodies, the most successful of which is the Materials Research Society (MRS), USA (1973). MRS has now given rise to the International Union of Materials Research Societies (IUMRS). The book similarly explores the history of academic departments in materials science. The first department to bear the name materials science came into being in 1958 in Northwestern University at Illinois, USA grafted onto the then existing Department of Metallurgy. Morris Fine was the visionary responsible for this first move, which was to bring about an avalanche of metallurgy–materials science conversions around the world. Cahn points to the helpful circumstance that Fine had studied 'quantum mechanics and statistical mechanics as a graduate student'. Also devoted is a small chapter for commentary on the databases so useful for physicists, chemists, crystallographers and physical metallurgists. Central to physical metallurgy are phase diagrams, whose first major compilation was *Binary Phase Diagrams* by Max Hansen in 1936, which has undergone revisions and generated successors published by the American Society of Metals, a series continuing and covering substantial ground in ternary and quaternary diagrams.

Omnibus encyclopedias of materials science and engineering (1986), of advanced materials (1994) and of materials (2001) at the broad end of the spectrum, and those in more specific domains in the field such as the materials selection charts by Ashby, first as a compilation in 1992, then by Ashby and Abel in 1995 to include those for high temperature service and more recently by Ashby and Maine (2000) dealing with selection reckoning with financial costs, are important landmarks. Whether we consider the way the journals diversified, or the manner in which the academic departments were transformed, often not without internecine battles, or the appearance of the different databases, there is a parallel between these developments and the emergence of materials science itself and the phenomenon of its differentiation. Not only instructive history, which is the theme of the book, but also interesting sociology associated with some of these developments in the academic world have been tellingly brought into particular focus in Cahn's inimitable asides.

The book is rich in many qualities and in its varied coverage, as already indicated. Two other general features also deserve particular mention. The distinguished author has rendered yeoman service by painstakingly providing references to key papers and various texts and books from the earliest times to this day, and valuable surveys. The earliest references are to Biringuccio (1540) who was 'the first craftsman to set down on paper about the preparation and working of metals and alloys' and to *De re metalica* (1556) by Georgius Agricula, the German thinker regarded as the father of geology. At the other end of this mind-boggling time-span are references to most recent publications in 2001.

In the other unique feature of the book, we are exposed to an inspiring cavalcade of great personalities but for whom materials science would not have obtained its substance, scope and status and its vast range of ramifications underpinning almost every functioning element in the modern world. Cahn, who has delved into biographies of several of these landmark thinkers, highlights interesting facets of their lives: for instance, that some of the all-time great scientists started off with education as engineers; Josiah Willard Gibbs (mechanical), Paul Dirac (electrical), John Cockroft (electrical) and Ludwig Wittgenstein (aeronautical). Gibbs was exceptional in that he preferred to be a lonely soul, not married and hardly interacted with anyone in the world outside himself. Imagine the power of a mind such as Gibbs', given that in our time so much value is attached to cooperative science and to holding and attending conferences, that, working alone and 'quitely', he comes up with his classic paper 'On the equilibrium of heterogeneous substances'. Cahn appropriately points to Newton, also a bachelor, who toiled in his 'quasi-monastic cell in Cambridge'.

I am tempted also to mention the reference made to a conversation between Dirac, for whom mathematical beauty was a test of truth, and Oppenheimer. Knowing that poetry fascinated Oppenheimer, Dirac asks him why poetry? To which Oppenheimer replies: 'in physics we explain in simple terms what no one understood before, with poetry, it is just the opposite'.

We similarly become acquainted with giants of physical metallurgy like Gustav Tammann, whom physical metallurgy students would know by the gadget called Tammann furnace with graphite as a heating element. Cahn's story tells us that this giant (also in build) of a scientist, who pioneered the experimental determination of phase diagrams, himself worked on 1900 alloys! The diagrams were arrived at using simple techniques like thermal analysis and optical metallography, as X-ray diffraction had not been discovered yet. But he was no easy man to deal with, as evidenced by frequent outbursts when some of his many students in his laboratory failed to measure up to his own gigantic capacity for work. Tammann's work constituted the core of an important transition, a shift from chemical to physics aspects of metallurgy.

However, materials chemistry has presently staged an impressive comeback with such developments as supramolecular chemistry, combinatorial materials synthesis, electrochemistry and the associated battery and fuel cell materials and novel materials exemplified by molecular films, fullerenes, nanotubes and manganates with colossal magnetoresistance. Naturally Cahn has in this book a chapter with the title 'Materials chemistry and biomimetics'. It was heartening to read in this chapter a laudatory reference to a leading Indian scientist, C. N. R. Rao, as one of the 'greatest modern exponents' of solid state chemistry.

To give the prospective reader a flavour of Cahn's presentation of the personality traits of several pioneers, let me give one more example. It is what Polanyi did with his 'discovery publication' on dislocations. Three scientists, Michael Polanyi, Geoffrey Taylor and Egon Orowan, simultaneously reached the same conclusion that dislocations had to be 'invented' to reconcile the large mismatch between the stress calculated from first principles and that observed experimentally, for the stress needed to plastically deform a crystal, as well as to explain work hardening. Cahn refers to Polanyi's account of this seminal scientific contribution. Polanyi's paper had been ready several months ahead of that of Orowan's, with whom Polanyi happened to be in contact. On learning that Orowan's ideas were taking shape, Polanyi voluntarily waited so that the papers by Polanyi and Orowan appeared side-by-side in the same issue of *Zeitschrift für Physik*. The professional morality practised here seems to me as significant for all seasons, as does the discovery by these celebrated authors.

I have referred to the above to provide in this review a sample of the author's endeavour to bring in something specially meaningful about the scientists themselves, while describing their major contributions. This fascinating aspect runs throughout the book in which we encounter numerous great names from the beginning to the end of the period covered. This is understandable, because the author's extensive journeys, and his own nature, have brought him into close contact with many scientists, indeed. Cahn has thus lent his work a rare and appreciative sensitivity to the achievements of his fellow scientists, past and present, and an uncommon acumen with which he unfolds the context in which he places both the person and his (her) science.

It is said of history that its value lies in the lessons that it teaches. This provides a perfectly legitimate motivation to study history, so that we may appreciate just which findings were crucial to the science of materials and learn about the stages of their subsequent development. However, why should anyone worry about the history of how discoveries came to be made? For several very good reasons, in fact. I believe that the best way to learn or to teach a difficult topic is to go back to the discoverer and to read his original paper describing the backdrop to his findings and his own struggle to concretize them. A few periodicals published some of these classics. Cahn's book is not about just one, but several classics. This approach is bound to prove successful in motivating future students to be drawn to materials science. In this respect the book recommends itself to all institutions teaching materials science, their teachers and students. Much more emerges, however, from Cahn's gripping, analytical approach. Let me bring up here Cahn's attention to Pasteur's principle that 'accident favours the prepared mind', which is an important lesson to learn. He illustrates this principle with a telling collation of surprises in materials science, which triggered discoveries. The invention of dislocations by Orowan, Polanyi and Taylor, Griffiths' illustration of the role of surface cracks in brittle fracture of strong solids, Frank's association of screw dislocations with crystal growth, and Keller's proposal of folding of polymer chains constitute a set of astounding discoveries springing from a challenge to explain surprising experimental observations flying in the face of known theories. Embedded here is the precious value of learning the 'how of the discoveries', an answer to the question raised. One more related lesson. Once Frank explained the appearance of growth spirals, a mineralogist was the first one to provide such photographs of growth spirals on the surface of beryl crystals. So also followed those of the others. But none of them had thought the spirals as anything so significant! Cahn points this out as a fine illustration of the principle that 'observers often do not see what is staring them in the face!'

Development of products too has its interesting background of notable and instructive events. An excellent example Cahn provides in this context is the progression that electric lamps went through. The beginning here is traceable to the work of a brilliant metallurgist, nay a physical chemist! Thomas Edison made the first successful incandescent lamp employing a carbonized filament (1879). Then came Irving Langmuir. He joined GE Research Laboratory in 1909 and solved the problem of design of incandescent lamps by elucidating the role of the inert gas filling in counteracting metal evaporation and suggesting optimum configurations of coiled filaments. While the discoveries of Joseph Henry in America and Michael Faraday in England resulted in electromagnetic induction leading to invention of the dynamo, it was in 1911 that GE commercialized lamps made with non-sag tungsten filament developed by William Coolidge, which proved an instant success. The challenge to and response of industrial design is superbly described by the battle between electric and gas lighting and the competition between tungsten filaments and Nernst's conductors based upon oxides such as zirconia and yttria. Obviously these wars were won by electric lighting and the tungsten filament which we now take for granted.

X-ray diffraction and crystal structure determination were important precursors to materials science. While Lawrence Bragg determined the crystal structure of NaCl and other ionic crystals, the first metallic material whose structure was determined in 1923 using a single crystal was that of white tin by Michael Polanyi. That carbon was a natural alloying element of iron came also to be known through X-ray diffraction and measurement of lattice parameters. The first determination of the crystal structure of an electron compound, Cu_5Zn_8(21/13), was by Westgren. Alongside crystal structure determination, crystallography really grew wings in the shape of crystal physics, e.g. analysis of anisotropy, and of crystal chemistry, e.g. phase transitions in solid state. These developments have resulted in as many as 25 Nobel prizes. Even so, as Cahn shows, crystallography was not accepted as a full-fledged subject for an undergraduate programme in a university like Cambridge. (In this same university, colloid science succeeded, albeit for a short time, in occupying a full-fledged department, ostensibly as a bridge between chemistry and physics and biology, only to vanish later!). The greatest contribution of crystallography perhaps is that it cuts through disciplines. Many of its votaries were the first to have delved into *borderless science*. For example, Dorothy Hodgkin, a chemist, used X-ray diffraction, then typically a physics technique, to unravel the crystal structures of biological compounds such as vitamin B-12 and insulin. To this day crystallography and diffraction techniques remain an essential tool in the hands of structural materials scientists coming from different backgrounds.

The understanding of materials required not only X-ray diffraction and crystal structure analysis, but also direct observation techniques. Thus, materials science could be said to have taken birth when Walter Rosenhain first observed the microstructure of a metallic specimen in an optical microscope and showed that metals consist of small crystal grains. In plane sections, these metal grains were characterized by many-sided polygons. In three dimensions, they were polyhedra. In what was perhaps one of the first comparisons between different categories of materials (Cahn's book sparkles with several such comparative descriptions that are so important for understanding diverse materials), Cyril Stanley Smith compared metallic polycrystals with soap bubble arrays and analysed topological relationships involving numbers of faces, edges and corners of polyhedra in contact. His analysis of frequency distribution of polygonal faces with different edges per face from such simple experiments contributed to some more foundational blocks of the edifice of modern materials science. More and more observational tools became available. The examples of the development of the scanning electron microscope, a product of collaboration between the University of Cambridge and Cambridge Instruments Company in England, and the electron microprobe analyser, originating from the doctoral thesis of Castaing, a French physicist who also went on to build the first instrument in Onera (a French Aeronautical Laboratory), highlight the value of the university–industry collaboration and the collaborative endeavours between university and national laboratory in the development of materials science.

The quintessential development of transmission electron microscopy by Peter Hirsch in Cambridge was the starting point of an in-depth analysis of microscopical observations at high resolutions. The famous paper by Hirsch, Whelan and Horne for the first time unveiled moving dislocation lines. This development was possible because of a superb combination of an advanced experimental technique and an understanding of the complex diffraction theory underlying image formation in the electron microscope used in the transmission mode. The story of having to *see* dislocations *to believe* them is 'as important to materials science as for particle physics'. Cahn describes the past parallel of Wilson's cloud chamber, which was invented when he observed natural clouds while mountain-climbing. His revelation of practical tracks was a telling answer to skeptics who did not hesitate to protest, 'who has seen a gaseous molecule or an atom?' With robust analytical instruments based on wavelength dispersion or energy dispersion added to the microscopes, one can now not only see, but also carry out compositional analysis of the features observed. Tools for imaging and analysis have continued to be developed. The scanning tunnelling microscope and its derivative, the atomic force microscope, the field-ion microscope and its derivative, the atom probe and the more recent derivative of the scanning electron microscope (SEM) called orientation imaging microscopy have unprecedentedly empowered the experimental materials scientist. As Cahn puts it, today one can not only *see* individual atoms, one can *contact* an atom, *lift*, *transport* and *redeposit* the same atom under visual control. This is almost like saying that man has now not only seen God, but has played dice with Him!

Microscopy for imaging as well as the range of analytical tools for chemical analysis have become fundamental to any materials science laboratory, and for that matter, to most science laboratories and institutes. The underlying impact is that they, more than any other experimental tool, have seen at once physicists, chemists and biologists access them. (Nearer home, my heart warmed up when I saw in our laboratory at the University of Hyderabad, a modern SEM being used by a plant scientist.) Their contribution to the development of materials science as a discipline is immeasurable. Observing and analysing microstructures, Cahn emphasizes (in the Epilogue), constitute the 'central component that best distinguishes Materials Science and Engineering from other disciplines'.

The emergence of the so-called functional materials marked a defining phase of differentiation of materials science, as distinct from structural materials (or engineering materials). In a full chapter, Cahn outlines how this development marked a shift away from the UK and Europe to USA and Japan. Nor did just this shift occur, there occurred also the emergence of industrial laboratories, traditionally engaged in the so-called applications R&D, as stars in the firmament of fundamental discoveries. A stellar figure in this respect was Mervin Kelly, Director of Research Laboratories at Bell Laboratories, who in 1936 set up an independent group devoted to physics of the solid state and insisted that his scientists focus on fundamental aspects! Eleven years later, in 1947 Shockley discovered the transistor, the fundamental building block of the Information Age. The 'function' of the transistor required that silicon be dislocation-free, which was made possible by a physical metallurgist Dash, and impurity-free, which was achieved by Pfann, a graduate in chemical engineering inspired by another physical metallurgist, Champion Mathewson. Materials science and materials scientists come alive in these events of monumental significance to the modern technological world.

Once the transistor was invented, semiconducting devices came to be rapidly developed and improved and fundamental physics research experienced a kind of renaissance. Cahn's chapter on this topic provides a flavour of these developments, including quantum size effects and the engineering of heterostructures. With wide-ranging applications in modern devices, functional materials research, pertaining to not only semiconductors but also electrical ceramics, magnetic ceramics, computer memories, optical glass, liquid crystals, and the like, began to dominate in the recent decades and in a way as to upstage attention to structural materials. With the bulk of research funding being currently invested in functional materials, will research on engineering materials be given up? According to our knowledgeable author, certainly not.

The leadership of Mervin Kelly at Bell Labs has a parallel in the visionary directorship of Gilles Holst, a physicist at Philips, the Netherlands. But for the magnetic ceramics that came to be thus discovered through the work of Snoek, Verwey and Neel, 'the factory of memory stores' at North American Philips could not have happened, nor the subsequent developments in computer memories. Glories of industrial science began to abound. Incandescent lamps (GE) have been earlier mentioned. Key innovations include xerography, laser printing (the earliest precursor of this coming from the Tungsram Laboratories in Budapest), glass-ceramics (Corning Glass) and optical fibres (Standard Telephone Laboratories, England), Invar, the only metallurgical achievement to have won a Nobel Prize (Imphy Laboratory), and the oxide superconductor (IBM), and this glorious chapter is bound to extend into the future.

The fifteen chapters of the book cover the following fifteen topics: (i) Genesis of a concept, (ii) The emergence of disciplines, (iii) Precursors of materials science, (iv) The virtues of subsidiarity focusing on the role of parepistemes in materials science, (v) The escape from handwaving, (vi) Characterization, (vii) Functional materials, (viii) The polymer revolution, (ix) Craft turned with science, (x) Materials in extreme states, (xi) Materials chemistry and biomimetics, (xii) Computer simulation, (xiii) The management of data, (xiv) The institutions and literature of materials science, and finally (xv) Epilogue.

While most of the chapter-headings provide a straightforward indication of their contents, some of these are intriguing and will bear a bit of my effort at their demystification. The title 'The escape from handwaving' has been used to highlight quantitative theories with the examples of dislocation theory and atomic structure of grain boundaries, calculation of phase diagrams (CALPHD), deformation mechanism maps and other selected quantitative triumphs. An excellent example is the way uranium metal came to be abandoned as reactor fuel, because of its own inherent thermal expansion anisotropy and the contribution of studies on radiation damage to 'broaden the domain of materials science'.

The chapter on 'Materials in extreme states' deals with extreme treatments (rapid solidification and its products, including bulk metallic glasses), extreme microstructures (nanostructured materials), surface science at ultrahigh vacuum, extreme thinness (thin films) and extreme symmetry (quasi-crystals). Among all of these post-war developments in materials science, Cahn foresees something of the future of materials science and technology in nanoscience and nanotechnology.

Cahn is a master craftsman of the English language and in this respect he excels himself in the titles 'The virtues of subsidiarity', and 'The role of parepistemes'. Cahn himself explains these words. Parepisteme derives from episteme, meaning a domain of knowledge and the prefix 'par (para)' stands for subsidiarity. Subsidiarity refers to topics off the mainline subjects of physical metallurgy or materials science and engineering. Examples of parepistemes chosen for treatment in a historical perspective in the book are experimental methods for growing metallic single crystals, diffusion, high pressure research, crystallography and superplasticity. Two perspectives emerge in this way, one pertaining to the value of open-ended research and the other to the usefulness of integrating knowledge from the subsidiary fields. In our own country, there is extensive advocacy only for purposeful research accompanied by the often veiled criticism of research done for its own sake. We will do well to note the developments that have occurred in materials science, or for that matter in any branch of science, are because someone initiated a piece of 'curiosity-driven research'. Cahn illustrates the benefit of integrating parepistemes with the recent work of Greg Olson on 'system-design' of steels, equally applicable to system design of materials in general.

Casting, metal forming and powder processing were age-old crafts used to shape metallic objects. In the chapter 'Craft turned to science', Cahn describes how each of these operations practised from time immemorial evolved into 'new metallurgy' in modern times. Bruce Chalmers was responsible for creation of the science of solidification. Similarly, understanding of deformation mechanisms following the discovery of dislocations, the birth of fracture mechanics with Griffiths' trail-blazing ideas and the understanding of the role of surface energy in sintering of metal powders beginning with the work of Paul Shewmon provided the scientific basis for longstanding metallurgical practices. Metals and ceramics are the only two classes in the world of materials that share a common structural basis. It is on this basis that strong steels, superalloys or strong structural ceramics came to be developed, as brought out in this chapter.

Polymers are molecular materials and cannot be manipulated with the same approaches as common to metals and ceramics. But there are topics, commonplace in metal sciences, which are also encountered in the context of polymers such as crystalline polymers, semiconducting polymers, phase transitions in polymers, polymer electronics and so on. Theoretical approaches like the use of statistical mechanics and experimental methods such as X-ray diffraction or spectroscopy are scientific tools which are profitably utilized by polymer scientists as well. However, polymer phase diagrams are yet to come about. As Cahn states, once the 'battery of concepts' underlying polymer science is grasped, these somewhat different category of materials can become equally friendly to the metal or ceramic-centred materials scientist.

The scientific process that consisted essentially of theory and experiment has recently acquired its third dimension, computation. Materials science is no exception to this major development. As Cahn's chapter on computer simulation shows, computational materials science evolved along the four paths of the Monte Carlo approach, molecular dynamics, variational approach and pattern development. To this, has to be added a bunch of numerical methods (e.g. finite element method) for simulating engineering operations such as metal forming. Microstructural design will increasingly depend on computational modelling and simulation. Calculation of phase diagrams (the CALPHAD approach), which now encompasses thermodynamic simulation, has developed into a powerful tool in the hands of the materials scientist and we are sure to use more of it all in the years to come.

The book is not, as may have become clear, meant to be a textbook of materials science, but any teacher or student of materials science would learn more easily, and better, topics in this field after he reads it. The book is not a research monograph on selected topics in materials science. But any reasearcher will not fail to be inspired to learn his lessons from this book through an appreciation of the backdrop to the important discoveries in related fields. Although it is meant to be an historical account embellished with sociological aspects, it is not written in a cavalier fashion. The book is the serious product of a colossal breadth of knowledge of materials science and scientists, reference to which time and again can provide a fillip to an active materials scientist to go forward with his exploration. The book contains the essential message, which Cahn's work over the decades also embodies, that the practitioners of modern materials science 'have proved themselves to be very open to the broader world of science'.

The city of Hyderabad, from where I am writing this review, boasts of a stupendous museum, a major attraction to tourists. It bears the name of its collector, Salar Jung (a minister in the Nizam's court), and is well-known as the largest individual collection of precious and semi-precious objects to be displayed in a museum. In what I see as a striking parallel, Cahn's book should also go down as the single largest individual collection of precious gems in a retrospective of materials science – gems from the history of this field, personalities, discoveries and events from which emerged this discipline.

Obviously, in Salar Jung museum, one does not find absolutely every type of artifact, nor does art from every country figure in its display. And yet innumerable objects of great interest, fascination and value, from many a country and period of history abound there. Cahn too repeatedly expresses his anxiety not to 'unbalance' the book and cautions the reader that his book is not an attempt at exhaustive comprehensiveness in its coverage. One may point out with fairness yet without carping that one would have liked to see more of any of the following: fibres, foams, composites, porous materials, biomimetics and biomedical materials, photonic and smart materials, and so on. One might also find a few impressive personalities not given enough attention to or missing from this book. But, surely, what the book does present, like Salar Jung museum, constitutes a treasure for now and for posterity.

Even as I finish this review of his book, there is good news that Robert W. Cahn has been awarded the prestigious *Acta Materialia* Gold Medal for the year 2002.

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