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Matter versus Materials: A Historical View

Cyril Stanley Smith

Not many years ago, I was a practical industrial metallurgist, and it is with some surprise that I find myself delivering a lecture in honor of a great historian. George Sarton pioneered in the application of the techniques of the historian to the then-neglected area of science. His immense energy, his proper regard to rigorously checked detail, his respect for the boundaries of his chosen period, and his insistence on comprehensiveness within these boundaries set standards for two generations of scholars in the United States and for the entire discipline on a world scale. I have done detailed research in both science itself and its history, but I want to use this opportunity to make some general remarks on man's attitude toward materials (in contrast to matter) throughout the whole of history. These derive from the fact that I happen to have lived at the time of some rather exciting developments in materials science-in fact even its formation as a recognizable area of knowledge-and have had a moderately intimate (if one-sided) look both at the recent history of science and at archaeologists' findings of the earliest uses of materials of many kinds. I see science reversing the trend toward atomistic explanation that has been so tri-

umphant in the last 400 years, and I predict a more human future based on the symbiosis of exact knowledge (which is by its very nature limited) and experience. This I do hesitantly, certain only that this is an important area for discussion at this particular stage of history. Materials provide a good illustration of the difficulties of applying exact knowledge to a complicated world.

Much of the history of materials has been rather dull, for man has usually been satisfied to make do with what he had, but there are three periods at which sharp changes occurred. These correspond to the first discoveries of the principal alloys and ceramic materials, the beginning of scientific explanation, and the very recent realization that, by the control of their structure, materials that possess almost any property in high degree can be designed and produced for special applications.

The Discovery of Materials

What Peter Drucker (1) has called the first technological revolution began more than 7000 years ago in the Middle East, where there arose an appreciation of the possibilities of technology combined with a pattern of social organization that both allowed the necessary

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specialization and provided the necessary superstructure for its exploitation and its control. Anyone who studies the reports of the major archaeological excavations, or, better, exposes his senses to the magnificent objects in clay or metal displayed in the museums of the world, cannot help but be impressed with the extent of real if untheoretical knowledge of materials displayed by early craftsmen. The well-shaped and decorated pottery from Chatal Huyuk (7th millennium B.C.), the gold jewelry from the royal graves at Ur (2600 B.C.), and the efflorescence of ceramic, stone, and metal art in Egypt and in Persia provide plenty of evidence that man knew, if he did not understand, a vast amount about the behavior of materials under chemical, thermal, and mechanical treatment.

Practically everything about metals and alloys that could have been discovered with the use of recognizable minerals and charcoal fires was discovered and put to some use at least a millennium before the philosophers of classical Greece began to point the way toward an explanation of them. It was not intellectual knowledge, for it was sensually acquired, but it produced a range of materials that continued to serve almost all of man's needs in warfare, art, and engineering continually until the end of the 19th century A.D. It is of basic significance for human history that, from the cave paintings on, almost all inorganic materials and treatments of them to modify their structure and properties appear first in decorative objects rather than in tools or weapons necessary for survival. Esthetically motivated curiosity, or perhaps just play, seems to have been the most important stimulus to discovery. The men who first produced basic changes in the very nature of common earths and stones by heating and mixing them must have felt an almost godlike power. Rare materials of many sorts are intimately associated with magicians' practices. They have long been used in the decoration of temples and churches to promote religious feeling and in palaces to inspire awe.

Through most of European history, since the Renaissance, both connoisseurs and historians of art have reserved their highest praise for painting and sculpture, and the most marvelous artistic uses of materials have been designated "decorative" or "minor" arts. However, the recent trend toward nonobjective art has been accompanied by a new appreciation of the esthetic richness in tex-

tures, colors, and other physical properties of materials. Such properties and the technologies derived from them have been appreciated far more in the Orient, both in the Middle East where it all began, and especially in the Far East. Chinese, Korean, and Japanese craftsmen in stone, wood, clay, and metals have sensitively used the subtlest properties of plastic and viscous flow, of crystallization, surface tension differences, and color changes resulting from ions in various states of oxidation and polarization. They have enjoyed the beauty conferred on a surface by chemical degradation and the irregularity that comes from fracture, deformation, and sectioning of polycrystalline materials. This sensual awareness of the properties of materials long preceded the Taoist and Ch'an (or Zen) philosophies into which it was formally incorporated.

The main characteristic of today's science of materials is a concern with properties and the dependence of properties upon structure. This is exactly where the story began. The history of materials has been a long journey in search of knowledge in strange and difficult terrain, finally to return to the familiar scene with vastly better understanding. Yet most of the histories of science are quite unconcerned with the structure of atomic aggregates, but rather deal with the basic philosophic question of the existence of matter, and later, as chemistry evolved, with questions of composition. Historians of science commonly regard as their central theme the throwing over of the Aristotelian principles and their replacement with analyzable elements and with weighable atoms. What a triumph it was to discard earth, air, fire, and water and to find atoms of silicon, carbon, hydrogen, and oxygen! Matter cannot be understood without a knowledge of atoms; yet it is now becoming evident that the properties of materials that we enjoy in a work of art or exploit in an interplanetary rocket are really not those of atoms but those of aggregates; indeed they arise in the behavior of electrons and photons within a framework of nuclei arranged in a complex hierarchy of many stages of aggregation. It is not stretching the analogy much to suggest that the chemical explanation of matter is analogous to using an identification of individual brick types as an explanation of Hagia Sophia. The scientists' laudable striving to eliminate the evidence of the senses has sometimes produced a senseless result. But if exact

science is used to illuminate empirical experience, and if experience is used to temper the extrapolation of the simple ideal systems of the scientist, then indeed we have real knowledge. Some materials scientists and materials engineers (both very recent professions) are, I think, beginning to see this. Their concerns are more than interdisciplinary, for they add a measure of art to discipline.

The Philosophy of Matter

The simple direct approach to materials is evident in the writings of the earlier Greek philosophers (2). Democritus (400 to 357 B.C.), following Leucippus, held that the distinguishing characteristics of materials depended upon three distinguishing characteristics of the aggregation of their parts---shape, order, and orientation. Such a relation, if not a theoretical dependence, must have been obvious to every stonemason, smith, or foundryman who used texture (revealed on a fractured surface) as a criterion of quality of both his raw materials and his products. These simple truisms, however, disappeared on further elaboration. Concern with real states of aggregation got lost in the search for the ultimate nature of matter. The Pythagoreans and Platonists seem to have regarded the numerical aspects of form as more important than form itself (as perhaps they should be to a philosopher).

It is the same with qualities. Aristotle in discussing his predecessor Empedocles (455 to 395 B.C.) says-quoting the most recent translation of Gershenson and Greenberg (3): "Empedocles was also the first to say that the elementary constituents of the matter in the universe are four in number, although he does not treat them as if they were really four separate substances. Instead he treats them as if they were only two-heat substance on the one hand, and on the other hand dry dust, colorless gas, and clear liquid (4) (whose properties contrast with those of heat substance), all dealt with like a single substance." There could hardly have been a clearer statement that energy and the three main states of aggregation of matter-solid, liquid, and gas-are the important things to consider. Later philosophers gave special meanings to these constituents and disguised their simple physical meaning in almost occult principles.

In Aristotle's own treatment of mat-

ter, the four material elements of Empedocles are derived from various combinations of four primary qualitieshot, cold, dry, and moist. Thus, earth is cold-dry; air, hot-wet; fire, hot-dry; and water, wet-cold. Structurally, Aristotle does no more than distinguish between visibly homogeneous and hetergeneous bodies and invoke the presence or absence of pores to account for some properties. However, Aristotle's reference to the distortion of ceramic ware in the kiln and his puzzling discussion of the melting and solidification of wrought iron in the steelmaking hearth leaves no doubt that he had observed workshop processes in some detail, and the 18 qualities of homoeomerous bodies that he chose to explain in detail in his Meteorologica, are just those fine points of behavior that would be noticed in a workshop. They are: solidifiable, meltable, softenable by heat, softenable by water, flexible, breakable, fragmentable, capable of taking an impression, plastic, squeezable, ductile, malleable, fissile, cutable, viscous (the converse of which is friable), compressible, combustible, and finally, capable of giving off fumes. He gives examples of materials possessing each of these qualities and the converse ones, and explains them in terms of the relative content of his four elements.

This redundant list of properties is not the neat classification of a philosopher. It reads more as if it were based on a conversation with a workman whose eyes had seen and whose fingers had felt the intricacies of the behavior of materials during thermal processing or as they were shaped by chipping. cutting, or plastic deformation. And the attributions of the proportions of the elements were an attempt to assign a measure of solidity or fluidity: it was more physics than chemistry, and it related more to real materials than to the fundamental nature of matter. The very word used by Aristotle for matter in general, hyle, was simply the word for wood or lumber, the common material of construction with real tangible properties.

The Chinese philosophy of matter, as it began to take definite form in the time of Tsou Yen (350 to 290 B.C.?) was based even more tangibly on the properties of materials. At the beginning the five elements, earth, wood, metal, fire, and water, were associated with phases of temporal cycles, but it will be noted that they also constitute a tribute to, and a classification of, the materials familiar to the workshop of the potter, the carpenter, the smith, and the dyer. As in the West, later Chinese philosophers got away from the artisan's sensual approach to matter and they developed an elaborate series of sequential relations between the elements and a complex system of symbolic correlations with seasons, tastes, smells, and much else—even including politics (5).

Histories of philosophy are full of discussions of the development of the concept of matter, yet hardly at any point do they touch on the nature and properties of materials. Atoms and the qualities that accompany their aggregation became pure exercises in thought, with the significance of monism and pluralism more important than the visible, tangible aggregations that, in the craftsman's hand if not in the philosopher's mind, were directly relatable to useful properties. Through most of history, matter has been a concern of metaphysics more than physics and materials of neither. Classical physics at its best turned matter only into mass, while chemistry discovered the atom and lost interest in properties. Only in the last few decades was it possible for solidstate physics to mature and to merge with a growing technology as attention turned again to materials and to qualities, which had now become measurable properties.

For 19 centuries after Aristotle, virtually all thinking about matter was expressed in terms of his elemental qualities; then came a period in which all advance arose from demolishing the misunderstanding that had accumulated in his name. During both these periods sensitivity to the wonderful diversity of real materials was lost, at first because philosophical thought despised the senses, later because the more rigorous experimentally verifiable thought patterns of the new science could only deal with one thing at a time. It was atomistic, or at least simplistic, in its very essence.

The practical world, of course, continued to exploit materials regardless of the state of science. The Greeks with all their sensitively shaped ceramics, sculpture, and buildings, and the Romans with their large-scale military and engineering enterprises made good use of the materials that had been discovered one or two millennia previously, but they added few new ones. Development was only in the economy and scale of production. In the Middle East, however, the ancient techniques were elaborated to some extent. In the working of steel, artisans of this region were par-

ticularly effective, as the crusaders who encountered the Sword of Islam learned painfully. Still farther east, in China and especially in Japan by the 13th century A.D., techniques of steelmaking rose to unsurpassed heights, but this had no influence on European technology or science.

Alchemy and Iatrochemistry

Greek philosophy-Stoic, Gnostic, as well as Aristotelian-had a lusty if deformed child in alchemy, which reached its height in the 16th and 17th centuries A.D. Much of alchemy seems to belong to the history of religion and psychology more than to the history of the physical sciences. The alchemists' attempts to relate macrocosm to microcosm, their extensive symbolism of sacrifice, corruption, death, and resurrection had an integral beauty that one must admire, but they helped mysticism more than metallurgy. Nevertheless, though chemists can legitimately scoff at the alchemists' attempts at transmutation, physicists should not, even those who are not concerned with nuclear reactions. Transmutation was a thoroughly valid aim, a natural outgrowth of Aristotle's combinable qualities, and its truth was demonstrated by every child growing from the food he ate, by every smelter who turned green earth into red copper or black galena into base lead and virginhued silver, by every founder who turned copper into gleaming yellow brass, by every potter who glazed his ware, by every goldsmith who produced niello, by every maker of stained glass windows, and by every smith who controlled the metamorphosis of iron during its smelting, conversion to steel, and hardening. Such changes of properties, seen physically, are transmutations, but they are not chemical in the purified modern sense, and the chemistry had to be clarified before the physics could be studied. The impossibility of making real gold lay in the necessity of duplicating all of its properties simultaneously, but taken separately the malleability, reflectivity, color, thermal conductivity, in fact practically everything but the density of gold, could be singly matched by suitable operations upon common materials. It must have been tantalizing and frustrating. There were many examples of the validity of the aim, and theory taught of the combination of qualities but gave no reliable way of achieving it. Many wonderful things must have been seen by the

alchemists in their mixings and heatings, more perhaps even than by the old craftsmen who sought only enjoyable esthetic effects, but they added little to transmittable knowledge. Their symbolic language had the effect that any security system has in hampering initiates as well as outsiders, and their theories, too firmly believed, closed their eyes to many phenomena and made visible what was not there.

Through the entire alchemical period, the workshop transmission of practical knowledge continued, of course. Many superb pieces of jewelry and other metal work were produced in the so-called Dark Ages. Early in the 12th century there appeared, for the first time in all history, a practical metalworker who wrote extensively of his craft. This was the pseudonymous Theophilus, a Benedictine monk, who gave a superb factual description of all the techniques of churchly decorative art and felt no need for a word of theory or for speculation about ultimate causes (6). The 16th century saw, among the flood of new works encouraged by the printing press, a sudden growth in practical literature at various levels. The most notable are the extensive books by Biringuccio and Agricola (7), who between them deal with all aspects of the winning of metals from their ores and their application to man's use. Both reflect the organized industrial framework that had replaced the craftsman's shop of Theophilus' day, but no new materials had appeared, and neither author felt the need of theory either to guide practice or to organize the description of it. Theory had, however, begun to change by this time, and significantly the change came from a man who had practical aims. The turbulent annoying medico Paracelsus (about 1491 to 1541) wanted to turn the main body of chemistry to the service of medicine, but, unlike contemporary metallurgists, he felt the need of theory and applied it both to the treatment of patients and to the preparation of his medicines, which he thought should be simple pure substances. Dissatisfied with the Aristotelian elements, he superimposed on them a new set of active principles-salt, sulfur, and mercury. These tria prima were not, of course, the materials known by those names, any more than the Aristotelian principles were really earth, air, and water, but they were to be combined in almost an Aristotelian way.

Paracelsus' principles were clearly suggested by three classes of real materials that have basically quite different characteristics. Mercury, primarily metallic but also liquid; salt, the ionic compound that gave its name to the whole class of salts; and sulfur, soft, easily melted, its molecules held together by Van der Waal's forces. These three materials exemplify three of the four types of interatomic bonding in today's quantum-mechanical theory of solids. Paracelsus in providing a more sophisticated version of the Aristotelian qualities showed a great insight into the nature of solids. From the physicist's point of view, if not from the chemist's, it was an important advance, but it was not one destined to develop, and only one of his principles survived to the 18th century. This was sulfur, which became a general principle of inflammability, a reducing principle, eventually phlogiston.

Corpuscular Philosophers of the 17th Century

A few decades after Paracelsus had redefined the chemical principles, the monopoly of qualities was challenged by a revival of interest in the structure of matter. The rebirth of atomism and the growth of Descartes' corpuscular philosophy have generally been treated in terms of the philosophical question regarding the ultimate divisibility of matter: I see them more as premature but well-based attempts to unravel the significance of larger structural units, the microcrystals, subgrains, and precipitated particles that the materials man today observes and controls. By the end of the 17th century, virtually every scientist took it for granted that matter was particulate in nature, but Newton had cast physics so strongly in the mold of quantitative mathematics that complex aggregates were beyond his reach, interest even. During the 17th century there was much delightful if unproductive speculation, but by its end the best scientists again abandoned real materials and settled for the study of only those properties of matter that are insensitive to structure. Theories of mass, acceleration, hydrostatics, elasticity, and kinetics found their way into every textbook of physics, but the promising studies of the strength of materials done by Musschenbroek in 1729 had few followers except among engineers, and then only after a delay of three quarters of a century.

During the 17th century, however, very many of the structural ideas that lie at the basis of today's approach to materials were suggested in a qualitative, conjectural way. It began with the rediscovery of Greek atomism, which was effectively used in the attacks on Aristotelian orthodoxy by Giordano Bruno and others, and slowly passed from philosophy to natural philosophy. Johannes Kepler in 1611 (perhaps following a suggestion of Thomas Harriot) described the various ways of stacking spherical particles into crystals (8). Hooke in 1665 showed how such a model would account for the various angular facets on polyhedral crystals. Huygens in 1678 related growth, cleavage, and optical properties to the stacking of spheroidal parts in calcite.

Descartes had an immense following, especially on the Continent, for his picture of the world based upon the aggregation of elementary (but not indivisibile) corpuscles. These particles resulted, he proposed in 1644, from the fragmentation of primary matter in his universal vortices and were shaped by attrition into polyhedra and rounded particles of various sizes, to leave a still finer form, his subtle element, the circulation of which served to compress the others together. The continental Cartesians were, shall we say, more imaginative than the proponents of the "mechanical philosophy" who precisely because of their restraint and disregard of metaphysical principles became so influential in England. Curiously, the Cartesian speculations contain very little about geometric crystallinity and a very great deal about the fitting together of irregular parts. There were spherical and polyhedral molecules; springy wire balls; denticulated parts which could slide over each other only when heat had separated them, thus accounting for the softness of iron at high temperatures; little needles of acid which could insinuate themselves between the parts of a metal; clumps of particles tied to each other tightly so that those on the surface were indifferent to external attack; felted and carded aggregates of fibers; loose structures that can bend, and tight structures that must crack; parts that can slide over each other without losing adherence; aggregates of more than one shape of particle that are stronger than aggregates of a single shape (9).

Every one of these structural concepts can be found in one form or other today, but they mostly relate to complex groups, not the atoms themselves, and are part of a coherent doctrine (10), not a collection of ad hoc assumptions to account for individual phenomena. Cartesianism was rightly discarded. Yet, just as the early craftsmen had intuitively felt the nature of their materials, the intuition of the corpuscular philosophers rightly suggested that the variety of behavior of matter was in some way related to the way in which its parts were put together. One of the last to use Cartesian structural concepts was the great Réaumur, who in 1722 made excellent practical use of the theory to account for the properties of iron and steel in terms of changes in contacts between different kinds of parts. Though he used the theory as a guide to develop two eminently practical materials-malleable cast iron and devitrified glass "porcelain"-he had no followers. Knowledge advanced in another way. Not structure, but composition was to be the center of understanding materials for the next two centuries.

Eighteenth Century and

Chemical Revolution

It has often been said that the revolution in physics preceded that in chemistry by a century. This is true only of part of physics, for the physics of solids lagged more than a century behind an equivalent level of understanding of their chemistry.

The 18th century, rather uneventful in physics, was one of the most exciting periods in chemical history, for it saw the change from principles to clearcut chemical elements determinable by quantitative analysis. The sulfur principle of Paracelsus had become associated with the qualities of oiliness and unctuousness, with combustibility, and with organic matter in general. Because such things usually contain carbon, it became also the reducing principle involved in metallurgical smelting operations. One of the various classes of earths postulated by J. J. Beccher was turned by G. E. Stahl in 1703 into phlogiston, which was putatively responsible for the profound physical effect of producing metallicity.

From Meissen in Saxony came not only the most successful European answer to the challenge of Oriental porcelain but a book, *Lithogeognosis* by J. H. Pott (1746), which experimentally classified earths into calcareous, gypsum-like, argillaceous, vitriable, or siliceous—still associating chemistry with qualities. But the main development in 18th-century chemistry was in the field of analysis. Even in the 16th century, the quantitative analysis of precious metals in ores and objects had been in an advanced state, for rather simple pyrotechnical operations (involving molten slags, sulfides, and the oxidation of metallic lead) would produce beads of pure gold and silver from almost anything that contained them. But the extension to other materials needed wet methods of analysis. These arose mainly in Sweden and eventually led to the new definition of an element. The growth of pneumatic chemistry led to the realization that the metallurgist's ancient charcoal fire had been a source of carbon and oxygen for chemical reaction as well as of heat. The subsequent story of the filling out of the list of chemical elements, of the quantification of the chemical atom and simple molecules, is a magnificent one, but it is too well known to need development here; it is of greater interest to consider what was not done.

Though the discovery of oxygen and the true chemistry of reduction was a triumph, in achieving it a physical feel for metals was put aside. It was not just stupidity that made a few chemists reluctant to abandon phlogiston. They were trying to preserve some of the quality beyond the composition. Though the oxygen atom is a rather big thing to overlook, it is nevertheless true that its importance lies in its physical effect of removing an electron from the state in which it confers metallic properties upon matter. In a way, the outer valence electrons of atoms correspond almost tangibly to the phlogiston postulated in the 18th century. Metals are metallic not because they do not contain oxygen but because they do have their valence electrons in the conduction band. Such internally free electrons confer ductility, conductivity, and other metallic properties. Their ready availability in carbonaceous and hydrogenous materials is responsible for the chemically reducing properties of supposed phlogiston sources. The electropositive elements soak them up. Bergman in his classic paper on the analysis of iron (11) used as a quantitative measure of the amount of phlogiston in various forms of iron the volume of hydrogen that was evolved on their solution in acid. Was he not physically right, for the yield would depend upon the electrochemical equivalent? Today we can handle phlogiston by itself; indeed we pump phlogiston through a resistor to generate heat and through an electrolytic cell to make metals. All of these possibilities were temporarily thrown aside when, after Lavoisier and Dalton, the determination of atomic ratios became the main aim of chemistry, and the role of the electron in solids had to be laboriously discovered by men of a different stamp of mind, quite unaware of its background in outmoded phlogiston.

Empirical chemical experimentation on materials continued, of course, long after chemical theory gave the main direction of research. Many problems that are of interest to solid-state physicists today were noted by practical chemists early in the 19th century, for example, the thermodynamic basis of elasticity in rubber, the catalytic effect of alumina surfaces, and various phosphorescent, thermoluminescent, thermoelectric, and photoelectric phenomena. Most of the electrical properties of materials were uncovered by simply observing, by new means, substances that had long been available.

Molecules and Crystals

Although the physical ideas toward which the corpuscular philosophers and experimental chemists like Boyle had been straining were slow to develop, the chemistry became clear and quantitative with Dalton's atomic theory. Here, too, an immense gain was accompanied by a not insignificant loss. The confirmation of Dalton's hypothesis was possible only by ignoring the large fraction of substances that do not conform to the law of definite proportions. Because of this, the whole relation between chemistry and metallurgy began to change. In the 19th century, metallurgists were foremost users of analytical chemistry, for they used composition, the presence of both major and minor alloying elements, to explain old mysteries such as brittleness in iron and copper, as well as to control the efficiency of production processes and to find new types of ore, but metallurgy lost the close association with the forefront of chemical research that it had had in earlier centuries, indeed from the very beginning. The separation, reduction, and refining of metals had provided the chemist with most of the reactions that taught him about the behavior of matter. For a whole century after Dalton, chemists' eyes were closed to all but molecules of stoichiometric compounds, and most alloys, to say nothing of sulfides and slags, are not of such definite composition. The bias toward reactions in aqueous solution was reinforced, although the fact that composition was not everything was shown by the newly discovered chemical

identity of the different physical forms of carbon and sulfur, and the existence of isomorphism between crystals of chemically different substances. The simple concept of the molecule was reinforced by every new discovery of the physical and the chemical behavior of gases and triumphantly vindicated by the kinetic theory of gases. In organic chemistry, the concept of the molecule was of utmost importance. Though it began as a notational scheme, molecular structure became a physically real model with Kekulé's benzene ring and with the development of stereochemistry. The very success of the molecule in gases and in carbon compounds, however, effectively limited any serious thought about higher levels of organization of either atoms or molecules in solids. Arguments about the crystallization of metals by vibration were carried out by engineers, not physicists.

Through most of the 19th century, the crystallographers, the physicists, and the chemists talked little to each other. Though Haüy's polyhedral boxes had become mathematical unit cells to contain molecules, the properties of crystals were attributed to the shape of individual molecules and to their orientation in space rather than to the manner in which they were stacked in the crystal. The concept of a crystal of a simple substance as a stack of balls is so familiar today that it is hard to account for the earlier disinterest in this model, especially since it was the first one actually to be proposed. Though the ball model was common among physicists, if not philosophers, in the 17th century, it had been replaced by little polyhedra (suggested by cleavage fragments) early in the 18th century. The mathematics of crystallography was, at first, the simple analysis of steps in such polyhedral packing and, later, of pointgroup symmetry, both done with careful avoidance of any suggestion that the mathematical units were chemical atoms or molecules. Wollaston said so clearly in 1813 (unaware at first that he was reviving the 17th-century view), but he had few followers until 1883 when Barlow (also an Englishman with an empirical bent) brought chemistry and crystallography together (12).

In the 20th century, chemical crystallography in both England and Germany was beginning to make great advances based largely on Barlow's concept, when the discovery of x-ray diffraction in 1912 suddenly gave a superb new tool for studying crystalline units and brought physics and chemistry together to take a look at real solids. By coincidence this discovery occurred within a few months of the publication of Niels Bohr's concept which gave physical meaning to the energy levels within the atom that had been revealed by optical spectroscopy, and it at once provided the means of extending spectroscopy to the shorter wavelengths and higher energies, needed for its full confirmation. From our viewpoint, x-ray diffraction also marks the beginning of a new concern on the part of physicists with the structure of atomic aggregates. Indeed, it marks the beginning of a reversal in the movement toward the ever smaller that had characterized physical science since its beginning. Structure had become measurable and with it arose an interest in those properties that were so sensitive to structure that they had previously been beyond the possibility of good "scientific" treatment.

To the physicist, even more important than the structure of the atomic framework is the structure of the electronic energy levels interacting within it, so elegantly treated by quantum mechanics. The electron, once discovered, quickly joined with old electrochemical theory to become the material basis of chemical valence. The Drude electron gas theory had some success in explaining metallic conductivities but otherwise had the same difficulty that the Rutherford atom had. The success of the quantum theory within the atom was soon followed by Schrödinger's generalized equation for aggregates, and for the first time in four centuries the fundamental approach to the nature of matter began to move upward in scale and complexity. A science of materials as distinct from matter became possible. Like molecular structure earlier, quantum mechanics began almost as a notational device, and even today physicists tend to ignore the rather obvious spatial structure underlying their energy-level notation, but the theory has the important basic quality of showing the dependence of energy on the entire structure; the structure within the atom--its outer shells at least-being dependent on its environment, and vice versa. Its very essence is hierarchical. It soon led to the explanations in terms satisfactory to the physicist of the various properties of solids that had been sensed and used so long before. It is still an ideal picture explaining matters in principle rather than in full detail, but the difficulties lie in the complexity of the calculations, not in the simplification of the model itself. The reasons for the

ductility and optical reflectance of metals, the hardness of diamond, the softness of sulfur, and the qualities which the early chemists had seen in the vitriols and salts were now apparent. All derive from the different patterns of the interaction of electrons and photons within the fields of the positively charged atomic nuclei, stabilized in a particular morphology by the interaction of the levels themselves. Matter is a holograph of itself in its own internal radiation.

Not the least important part of the new approach, forced by the obvious inadequacies of the ideal structure of crystalline matter that resulted from the first crystallographic studies by x-rays, was the focusing of attention on the role of disorder and imperfections, both mechanical and chemical. It was only after 1940, however, that physicists discovered the importance of the metallurgists' older naive concepts and empirical data on the behavior of grain boundaries and on the work-hardening of crystals (both currently explained by the interaction of dislocations within the crystals); on diffusion, which metallurgists had used for millennia in making brass, steel, and gilded surfaces (now seen to require vacant sites in the crystal lattice); and eventually electrical imperfections both in the form of ionic substitutions, vacancies, and local charge anomalies called excitons. Models based on each of these unit imperfections could be mathematically treated in the approved way. A field that particularly attracted physicists in the decades after World War II was that of semiconductors, and here it must be noted that the knowledge of the old craftsman contributed little: it was physics of a new kind, theoretical and practical men working together for complex objectives in which the physicist's passion for understanding was influenced by an acknowledged desire to be useful, perhaps even rich and influential, and this led him to a keener awareness that understanding things "in principle" was not always enough.

Metallography as a Harbinger of Solid-State Physics

The rapid advance of solid-state physics in the 1950's would not have been possible had there not existed a rather well-developed body of knowledge relating properties to the level of structure visible under the optical microscope. This realistic concern with structure was the metallurgists' particular contribution to science, for it brought back into view, via empirical but intelligent observation, some of the more complicated aggregates about which the corpuscular philosophers had speculated in the 17th century. This has been discussed at some length in my book A History of Metallography (13) and is only outlined here. For some reason the early microscopists had failed to find significant structure in metals, and even Réaumur's masterly study of fracture, mentioned above, had no followers, for most scientific metallurgists in the 18th and 19th centuries were involved in exploiting the application of chemical analysis.

Some interest in structure remained, however, on a practical level. Fracture tests continued to be useful especially in controlling the quality of iron and steel. Some disastrous railroad failures in the 1840's precipitated fierce arguments over the crystallization of metals by vibration. After a hint from geologists who had developed coarse crystalline structure in iron-nickel meteorites, the true microstructure of steel was at last disclosed. This was done in 1863-64 by Henry Clifton Sorby who was the first European to prepare metal surfaces by methods delicate enough to avoid the obliteration of the significant structure. Studies of metallography, as this branch of physical metallurgy became misleadingly called, took on renewed meaning after 1900 when Gibbs' thermodynamic principles were shown to be simply applicable to the analysis of the existence of phases. Scientists-mainly German chemists-undertook to determine constitution diagrams of innumerable binary alloy systems by mixed thermal and microscopic means. No rules of alloy formation were uncovered (ordinary valence seemed not to apply) and so much unrelatable data had been discovered that the chemistry of alloys was beginning to lose interest in 1912 when the new technique of x-ray diffraction opened up structure on a different level for exploration.

The relation of the visible microstructure of metals to useful properties, however, continued to be a popular activity among scientific metallurgists. Theories of deformation, of the nature of intercrystalline boundaries, of transformation mechanisms, and many other subjects popular today were advanced and discussed by metallurgists decades before physicists discovered that there was any interest in this scale of matter. But x-ray diffraction inevitably led the physicist into contact with the whole range

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of solids, and made imperfections unavoidably visible. By 1930 there had been postulated several different types of imperfection—those resulting from gross polycrystalline heterogeneity and various types of mechanical and chemical imperfections within an ostensibly homogeneous single crystal. These models provided satisfactory explanations of many age-old phenomena. An extremely fertile period of interaction between metallurgists and physicists resulted, now, fortunately, extending to those who work with ceramics and organic materials as well.

The new viewpoint is so potent that it has, perhaps, caused too many metallurgists to forsake their partially intuitive knowledge of the nature of materials to worship at the shrine of mathematics, a trend reinforced by the curious human tendency to laud the more abstract.

Nature of Materials Science

Even in the field where he was once supreme because he alone could make or build, the engineer is currently losing status to the scientist. Personally, I think this is temporary, partly because many people who are called scientists are simply users of computers with no more understanding than the old unimaginative users of engineering handbooks, but more because I see in materials engineering the germ of a new and broader kind of science, an attitude of mind, a method and a framework of knowledge applicable to many areas. The materials engineer, no longer the specialized smelter of ferrous or nonferrous metals. is now beginning to look at all materials competitively or rather comparatively. He is as likely to be interested in ceramics and synthetic organic polymers as he is in metals. His job is to find, to invent, and (or) to produce materials having the particular combination of properties (mechanical, magnetic, optical, electrical, and others, including economic) that is needed for a given service. The materials engineer's complex knowledge of what it is possible to achieve, involves him in the very center of discussion of most new projects, whether scientific, engineering, or social in nature.

The materials scientist has in large degree recaptured in more definite form many of the discarded intuitions of the past. He has returned to a direct and intimate concern with the qualities that fascinated man from the beginning, and the explanation of these properties is now seen to depend directly upon structure, that is, form. But significant structure is a mixture of perfection and imperfection. The imperfect aggregates are, on one scale or another, not much different from some of the aggregates that were postulated with undisciplined enthusiasm by the Cartesians. Phlogiston, which the chemists had to discard as an inadequate compositional reason for the difference between a calx and a metal has become the quantum theorists' conduction-band electron, quite literally responsible for metallic qualities.

The whole story of man's relation to materials involves the interaction between the simple and the complex, with all of the triumphs of science up to the present being in the direction of the atomistic (or at least simplistic) and all of the realities of matter being complex. The laws of science apply under definable circumscribed conditions. The transistor shows that simple things matching the mathematics can be made in practice, but most things that human beings deal with are complex systems that are the result of a long succession of single events, recorded in the emergent structure but in combination are essentially uncomputable. In practice it is necessary, therefore, for what exists to be measured grossly, using mainly sensual experience to reveal the cooperative effect of innumerable factors that are computable only in isolation.

The enormous success of the rigorous atomistic approach in the last three centuries has led us to expect continued illumination from the same approach. In the limited high-energy world below the atom it seems as if there are always particles below particles, but nothing so fundamental lies in the realm of concern to us aggregate humans, where the need is, now, for the study of real complexity, not idealized simplicity. In every field except high-energy physics on one hand, and cosmology on the other, one hears the same. The immense understanding that has come from digging deeper to atomic explanations has been followed by a realization that this leaves out something essential. In its rapid advance, science has had to ignore the fact that a whole is more than the sum of its narts

Polanyi (14) has strongly argued that biology is not reducible to physics and chemistry since the existing morphology of an organism, which provides the boundary conditions within which the physical or chemical laws operate, are physically and energetically indis-

tinguishable from other no less probable morphologies that have not happened to come into existence. This argument is valid and applies even to the much simpler aggregates of the materials engineer.

Science now relates of the two extremes of elementary atomistic physical chemistry on one hand and averaging thermodynamics on the other. But why cannot science develop a new approach encompassing the whole range? I am not as pessimistic as Polanyi, for I see in the complex structure of any material-biological or geological, natural or artificial-a record of its history, a history of many individual events each of which did predictably follow physical principles. Nothing containing more than a few parts appears full panoplied, but it grows. And as it grows, the advancing interface leaves behind a pattern of structural perfection or imperfection which is both a record of historical events and a framework within which future ones must occur. Deoxyribonucleic acid is simply a mechanism to save time in reaching higher levels of organization, though, of course, with severe limitation of possible structures. It is neither possible nor necessary to study all structures that might have existed, but there is need for studying more than a statistically averaged structure. Is there not possible an intermediate science using the structure that exists-important for no other reason than that it does exist-both as a key to history and as a framework for continuing process?

Hesitantly, in my ignorance, I predict the development of some new principles of hierarchy that will enable the effective resonance between molecule and organism to be explored: possibly the way to this may be pointed by the emerging science of materials, so incredibly simple beside biology but complex enough to demonstrate a kind of symbiosis between scales, the interwoven importance of both atoms and aggregates. Such things can be appreciated and understood only by a parallel aggregation of viewpoints, one intellectual, atomistic, simple, and certain, the other based on an enjoyment of grosser forms and qualities, but somehow the two must join as they do in matter. A few men will be in touch with both levels, but human capacities are such that most must specialize, and the liaison man will be far more important than he has been in the past when the greatest intellectual opportunities lay at the frontier. The scientist need not despair. He must become a little more of a whole man. He must restore his senses to a position of respect, though not in domination over his intellect, for each must supply something lacking in the other.

This approach would bring together fields that because of their special complexities have been unrelated; it would minimize the difference between the scientist and those who try to understand the human experience. It would incorporate the historian's interest in the past as the basis of the present and the artist's feeling for the complicated interrelatedness of things. Encouraging diversity but controlling disruption, it would suggest more viable political structures. Using man's mind, hand, and eye in coordination, it would be a thoroughly human activity. This conclusion, if not perhaps some of the details of my historical approach to it, George Sarton would have approved.

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