NOTES AND DISCUSSION

Adrienne R. Weill

REFLECTIONS ON MATTER AND MATERIALS

Our representations of the solid state have evolved more and more rapidly as the physicist has had at his disposal more deeply penetrating radiations with which to explore it. The successful use of the optics of luminous rays was followed by X-rays, then radioactive rays, including neutrons and electrons, leading to increasingly perfected models of crystalline structures characteristic of the chemical composition and the physical properties of matter.

To become materials, raw matter must follow a certain design. Far from being a degradation, technical use is a promotion insofar as it implies a body of precise knowledge and not an arbitrary or conventional choice. The diamond is a delightful substance indeed, but it is a choice abrasive as well. To the jeweler it is a sumptuous and unchanging stone, of a high price, which (to bring out its brilliance) justifies an artistic cutting, ably executed according to empirical rules with no direct recourse to theoretical knowledge of its structure. For the industrial manufacturer it is an

Translated by James G. Labadie.

abrasive so hard as to cut all other substances while showing in itself almost no signs of wear. And the metallurgist knows the sapphire as a substance which, when finely divided into particles on the order of a twentieth of a micron (the micron is the thousandth part of a millimeter), can be used to polish the hardest metals, like cast iron or some special brasses, and to provide, on surfaces from which the roughness left by the cutting tool has been removed, a microscopic view of the structure.

Whatever application may be envisaged, whether it be an appeal to taste or even to a very simple need, a purely empirical knowledge of the substance is sufficient for attaining the desired aim: the artisan will be able to achieve excellent results whether in the cutting of a gem or the abrasion of a surface by simply mastering the technique employed.

But let us suppose that because of some need, as may well occur in a world in which more and more complex techniques are required, the engineer seeks a matter harder than the diamond or capable of conserving its qualities at temperatures above 1,000° C. Nature will furnish him no satisfactory substance. He will then need to make a complete inventory of what he knows: to find out why the diamond is hard and how its hardness is acquired and may be increased—in short, to produce an improved version of a diamond.

The synthesis of the diamond, despite the hopes raised by the work of Moissan—remarkable in other ways—still belongs, though perhaps not for long, in the realm of mythology. The very undertaking of such a venture in the nineteenth century was, even for a scholar of fine reputation, to lay one's self open to criticism, to color with venality that "devotion to science" which seemed from the outside to be a condition essential to progress, if not to salvation.

Today, however, it seems absolutely normal that the resources of the greatest of laboratories be mobilized, in full view of all, for a technical improvement. Thus several months ago a matter harder than diamond was made in the United States; in the research laboratories of General Electric was born "borazon," legitimate child of scientists who successfully synthesized a matter of the same crystalline structure as the diamond, endowed with the same properties of hardness, and, in the bargain, enjoying important advantages over the natural product.

How did this happen? The broad lines of the development follow. Through examination by means of the diffraction of X-rays may be observed the manner in which are disposed the constituent elements of matter, atoms formed of a nucleus and the surrounding electrons. The atoms of carbon may be assembled in two crystalline forms, quite different in appearance and in properties. Graphite occurs naturally in black lamellated strips, lightly enough linked with one another to slip apart under slight pressure, somewhat like superimposed pages, while diamond, radically different to our eyes and senses, is hard, transparent, limpid.

Now the examination of graphite by crystalline analysis leads to a model of structure in which dense layers of atoms are held together by forces much less intense than those, equal in all directions, which hold together the same atoms of carbon in the diamond, according to a pattern of higher symmetry.

So, beginning with a chemical compound of the same crystalline structure as graphite, boron nitride, the American researchers (the word "savant" is scarcely used today) succeeded in transforming it so that the interatomic bonds were established in a different mode, precisely that of the diamond. This new matter, borazon, is possessed of a hardness superior to that of the diamond at ordinary temperatures, and this property resists much better the destructive action of heat, so that it loses none of its effectiveness above 1,800° C., while the diamond yields at about 900° C.

The progression from how to why, the development of *Homo faber* into *Homo sapiens*, is not always so clearly seen as in this case. There is no more reason to be proud of a successful venture than to be ashamed of a failure. The very life of the laboratory is made up of positive and negative results, and will be, so long as our knowledge remains insufficient to our needs and our hopes.

At any rate, we are constantly more aware of and alerted to how much we are lacking in the way of theoretical "pigeonholes" in which to classify the fruits of our experiments—or, what is worse, of how deficient are the pigeonholes we once thought to be well devised. How many times is the indispensable constant missing in the reservoir of our knowledge? And when we attempt to calculate the constant, it escapes us, changes, so that the task we were attempting to narrow down becomes even broader in scope.

One measurement error, yesterday insignificant, may, by reasoned criticism, lead on to a new path today; another line on the diagram is placed outside its theoretically assigned limits, and we have to open a new slot to account for this most recent observation. Examples in which a new and freshly painted pigeonhole, if we dare continue the metaphor, is opened precisely to receive the results of a test are still rather unusual—but we shall have occasion to cite remarkable contemporary instances.

Let us stop first at the most frequent case, that in which the experiment is made prematurely in the fullest sense of the word—before the mind is ripe. Returning to the centuries preceding the Christian Era, let us follow some Greco-Roman vessel carrying its cargo of amphorae to ancient Massilia. A submerged wreck lies off Marseille, near the isle of Grand-Congloué, explored and partly raised by Commander Cousteau and his associates. The ship's deck was protected by lead plates fastened with copper nails.

This copper—which the writer has had the good fortune to analyze—is of a purity we find astonishing in the twentieth century, aware as we are of the difficulty of extracting from oxydized and sulfurized ores a metal which, left to itself as matter, or left to its fate as a manufactured object, will resist corrosion (a more fitting word here might be "corruption") in proportion to its purity or absence of poisons. But this is on condition that it exist by itself. The proximity of lead in a saline atmosphere is fatal to copper. Thus the archeologists who followed the underseas expedition noted with what care the shipbuilders of the time sheathed the copper in lead "to avoid the voltaic effect." What represented for Volta a pile, a source of energy, did not fail to harass seriously the shipbuilders of Delos, and it took two thousand years for the obstacle to be turned to the advantage of the observer. If, then, in the daily practice of our own laboratories we still have many little nails to sheath, we may at least hope that there is sometimes an excellent reason for this, even though it may try our patience.

But let us return to the models of crystalline structure revealed to us by X-rays. For certain materials such as ordinary metals, the pattern is extremely simple. Symmetry is highly developed. Around a well-determined axis the figure in space takes the identical position two, three, four, or six times in a complete turn. The axis is said to have binary, ternary, quaternary, or hexagonal symmetry. And our knowledge is well represented by this symmetry—so well, indeed, that it is then easy to communicate by a tridimensional lattice, a model made of small balls and wire.

While ordinary metals, with few exceptions, are of simple and well-understood structures, the model becomes complicated as we approach the representation of organic compounds, whose molecules may contain thousands of atoms. And every virus, every protein, becomes a little world, the broad lines of whose skeleton we are only beginning to understand.

But when the metallurgist visits the galleries of the Palais de la Découverte in Paris, or any other institute of that kind, if he acquires an easy familiarity with these models of matter, if he can classify mineral species according to a readily accessible geometry, will he be better equipped to forge new materials? Without going this far, is he likely to penetrate deeply into the mechanisms of materials traditionally used for centuries without trying to substitute for them equivalents which are functionally more adequate?

The question took a sharp turn about twenty years ago. Intoxicated by successes achieved through diffraction of X-rays, crystallographers saw in their models an ordered representation of matter, well-arranged atoms, general laws applicable to structures of equal symmetry. For the simplest, such as those of metals, they knew clear and precise facts having to do with their mode of crystallization or the mechanism of their deformation or that of breaking down through cleavage. Reference could be made each time to that plane of the model with the highest density of atoms. In other words, in normal growth, the crystal was limited by those surfaces in which the atoms are nearest to each other. In case of constraint: traction, for example, deformation manifested itself through mutual glide of these same planes, whether one dealt with zinc or cadmium, where there is but one series of dense planes all parallel, or with copper, aluminum, silver, or gold among others, where there are three equivalent directions of planes of maximum density.

Forgetting for a moment what might separate geometry from reality, the savant took possession and control of matter and then tried to force nature to conform to the model in order to produce materials endowed with precisely those physical properties associated with the three-dimensional schema of the structure.

We mentioned earlier a striking example of the success which may develop out of research conducted in such a manner. Many others might be added, less simple, and of varying importance, from the vulcanization of rubber to the plastics and man-made textiles industries; in between is the permanent wave, practied in innocence by the coiffeur. But let us return to the model of metallic elements and see what the blacksmith found to his satisfaction—and to his dissatisfaction.

The model can be identified with the material only insofar as the latter is present in appreciable volume, at least several cubic millimeters, in a perfectly regular manner. The sole condition is that in the representation, which consists in repeating as many times as necessary and following three axes in space, the elementary pattern conserves its orientation. One is then said to possess a single crystal, and it is correct to attribute to this mass the characteristics recognized in the model; for example, the proper directions for the propagation of light if one is dealing with calcite—the Icelandic crystal described by Huygens—or, if dealing with a metal, the directions of easy glide.

Now the metallic materials in current use are not single crystals, and nature, except in moments of rare prodigality, does not provide them in a state of regularly organized matter. When man succeeds in extracting metals from the minerals in which they are disguised as oxides or sulfides, for example, he has at his disposal a liquid mass at high temperature which, on cooling, gives an agglomeration of more or less regular crystals, of highly variable dimensions, depending on the nature of the element and the treatment it has undergone.

The model is identified with but one of these grains, whose mass constitutes a polycrystalline aggregate, endowed with mechanical properties quite different from those of the monocrystal. In fact, a glide, for example, if begun in a grain, will propagate itself under the same force only insofar as it encounters no obstacle. But, between grains, frontiers separate two crystalline domains of differing orientations, so the glide has a much better chance of being stopped by the boundary than of continuing to spread. Thus the polycrystalline body offers much greater resistance to stress than does the monocrystal.

To compare the intrinsic properties of the metal in the material state with the structural schema, physicists have tried to produce the single crystal in a free state. They have successfully fashioned small bars of zinc, cadmium, aluminum, iron, copper, or still other metals and have compared this materialized model with the ideal structure (that represented by the model of balls and wire—the result of their analysis) for which the calculations of forces of binding and decohesion were valid.

As perfect as their single crystal was, it never conformed to the schema, at least not quantitatively. In its first approximation it followed the established rules: monocrystalline aluminum, carefully purified, bent under its own weight, traces of glide wrinkled its surface. Cadmium and tin, in round bars, were easily stretched, their sections flattened at the same time as the already known "cry" was heard, but identified this time with the separation of two atomic layers, thus with a mechanism millions of times lower than the limit of our sense perception.

What was no longer at all acceptable was the fact that the stresses brought into play were several hundreds or thousands of times inferior to those which had been calculated with all the already considerable resources of the physics of twenty years ago. So the ideal matter (the metallic single crystal of the time did not seem to figure properly among the materials), the matter of the physicists, corresponded neither to the model nor even to an embryo of something useful. It was an entity apart from nature and apart from the manufactured object.

Here, then, was the physicist at an impasse, the engineer puzzled. and, if some inspector of scientific method had passed by, he would rightly, under the circumstances, have given free reign to pessimism.

But some farsighted minds, assuming an intentional naïveté, asked themselves a question which today can only too easily be called simple (the comfortably placed historian enjoys a clear advantage over the laboratory worker). Instead of rejoicing at the sight of markings on the surface of the single crystal bars, they asked why certain of the billions of atomic planes had moved, while others had apparently remained in place.

Still mindful of the difficulties inherent in the preparation of the monocrystal, of all the precautions necessary to avoid the accidental growth of a grain-boundary here, a twin or a kink there, the physicist sought to discover whether through some stroke of bad luck his crystal, perfect as it might appear, might not contain some defects. The working hypothesis retained by the specialists was a double one: on the one hand, the presence of defects; on the other hand, the localization of these defects in the glide planes. In other words, the structural defect, just beginning to be taken into account and not yet identified, was already laden with responsibilities.

Moreover, if the data are closely examined, or, better still, if the attempt is made to construct a structural model with balls and wire—and let those who do not ordinarily indulge in three-dimensional games be warned that enormous quantities of wire are needed—glaring blunders readily susceptible to the physicist's criticism are apparent. In other words, the field of forces at rest represented by the static model is not to be thrown into disorder any which way.

In a scientifically established order the modes of defect are strictly limited by what our physical knowledge imposes. A violation of the miniumum interatomic distance of the model is indicative of enormous compressions, causes of explosion; if, on the other hand, these distances are exaggerated, the model sublimates and becomes gaseous. If only certain joinings of the three-dimensional model are retained and others suppressed, we will have thin sheets or fibers, a paste, or a liquid. The schema is not a game of wits; it is a material symbol fraught with significance.

And yet, if there is a defect, it must be invented. I say "invented," for to discover it we need something we do not yet have (although we are approaching it)—the possibility of observing the individual behavior of atoms.

Despite the restrictions imposed by the laws of physics, the scientist found two solutions, which, thanks to these restrictions, not only were exactly authenticated but were found to be fruitful beyond all hopes. The first type of defect consists in supposing that, at the time the links are juxtaposed to form the model, the artisan—whether it be nature or the physicist—is going to interrupt a lattice plane in the center of the mass. Instead of being formed of regular planes, all parallel and of identical surface, the model—or the crystal—will contain, for example, an extra plane in its upper part, one less in its lower part. The result in the structure will be what architects call a "squeeze." The upper part will be slightly compressed, the lower distended, but at a slight distance from this "dislocation" nothing more will be noticed.

But this slightly disordered model will enjoy completely different properties from those of the perfectly ordered model. The array of atoms terminating the plane of insertion will not be joined to its neighbors quite so rigidly as the one having an exact opposite. A very slight push will direct it toward a neighboring plane, which in its turn will leave half a plane without an opposite number, and so on. The effect will somewhat resemble that of a row of standing dominoes knocked down one by one when the first is upset against its neighbor.

And here we see the imagined mechanism giving a theoretically irreproachable interpretation of the glide phenomenon, observed in the monocrystal, save that, as meticulous experimenters will be quick to point out, it all happens in the mind of the physicist, while we, in the laboratory, observe neither the unhitching of the atoms nor the engagement of the glide.

Theoreticians do not stop here, but imagine another type of defect, a bit more difficult to achieve with wire. But it is achieved and proves most instructive. Suppose that we did not know how to construct the planes very well—here a pattern of squares with balls where the wires cross. When we superimpose these planes, which, for example, will all be raised toward the top, beginning with a row which we see end-on, like the middle of the magazine we are reading when the right-hand page is raised, we will no longer be able to follow a row from left to right without being at a given moment halfway between planes n and $n+1$. Thus our progression in the model will no longer be that of a circle in a plane but rather an unclosed circuit; the curve leads us to return not to our point of departure but to a point above or below. There will then be at the upper surface of the crystal a sort of monoatomic step linked to this helical, or, more exactly, to this screw dislocation. A precise meaning can be given to this invention by showing that it is concretized by a vertical push involving but one part of the crystal.

Nothing stops the theoreticians once dislocations have been invented; they study all the evolutions, all the variations according to the particular structures of the metals, and in the well-established order the dislocations find themselves at home.

There would indeed have been no possibility of reasoning about disorder if one had not already been formed in the school of order. Sometimes (as in electricity, for example) a discovery leads at least to the temptation to upset for teaching purposes the chronological order—to begin with the electron would be in a sense more rational than to begin with the laws of the establishment of electrical current. But for matter this is not so; on the contrary, the study of disorder conserves and validates the ordered model. This is true to such a point that, ever more sure of themselves, crystallographers sought a representation less fixed than that of the model of balls and wire to illustrate and communicate the results of the systematic analysis of disorder and of movements facilitated by defects of organization.

The success of the dynamic model merits our attention for a moment. It consists of a two-dimensional analogy, constituted by a raft of bubbles blown in a viscous soap-based solution. In the absence of any agitation the bubbles are arranged side by side, like the atoms of metal in the most closely packed planes of compact structures. Thermal agitation, which in matter causes atoms to oscillate around their rest positions, occurs when a glass rod (an agitator, in laboratory language) disturbs the raft of bubbles. Point defects are thus created, by the bursting of bubbles, for example, and result in more or less unstable dislocations which, depending on conditions, are propagated or anchored in the network. Springs may be maneuvered to produce shearing or compression on the raft. So we witness a cinematographic recording of the phenomenon with all the defects theoretically foreseeable. Whereas the theory had been judged overly daring, its illustration not only confirms it but even extends it, showing, for example, cases of reflections of dislocations by grain boundary which had been too daring to be advanced.

One of the most remarkable points brought admirably into evidence by the model is that of the possibility of stable configurations, of organizations of dislocations in arrays forming a well-defined type of boundary between two slightly misoriented domains.

About 1948, before any direct experimental verification of dislocations (the historian exerts his rights again), physicists of metals suspected this mode of arrangement and gave it various names; that of "polygonization" was to prevail, well representing the break in arrays of atoms which was substituted for distortion and which resulted from the rearrangement of the dislocations among themselves. At the same time an age-old problem, on which progress had been made for about a hundred years but which was still not completely understood, came again to the fore: the problem of crystal growth.

Nature, at once prodigal and miserly, furnishes man with such magnificent crystals as the diamond, quartz, and calcite; but, as soon as society accepts them as materials, it demands more and better ones. For optical instruments and telecommunications, then, the laboratory was called upon to provide these (non-metallic) single crystals, not always easily, but fairly satisfactorily produced by artisans. Let it be understood by this that, even though production were extended to the industrial level, the laws of growth could be determined only in practice. But this was fortunate, as the theoretical physicist could but offer laws accusing the solid of a reluctance to grow, which was well calculated to discourage any productive enterprise.

No matter how careful the calculation, from the simplest case—a monoatomic crystal growing from its slightly supersaturated vapors—the edifice progressed badly. There was imagined a layer growing on an already formed block, thus providing a step on which atoms of vapor came to link themselves to the already fixed atoms. To increase the speed of the phenomenon, the atoms reaching the surface must have more chances of being caught than released. According to a reasoning practiced (if not invented) by Huygens in its reciprocal form to interpret the cleavage of spar, the situation was improved by endowing the growth front with zigzags and kinks, offering the migrant atom not only two neighbors but three or four, each ready to provide additional bindings. The calculation then offered approximately the representation of the growth of a layer. But, once the layer was finished, a favorable fluctuation must be awaited in order for a new nucleus to be constituted, which, surrounded by its kinks, might serve as the beginning of a new layer. This delay, imposed by the knowledge of physical laws, caused all calculation to fail.

One of the promoters of the theory of dislocations, F. C. Frank (many others should really be mentioned, as science today has become so much a collective work), observing the struggle of his colleagues at the University of Bristol, suggested (perhaps half-jokingly—one never knows how great things begin to take shape in fine minds) that they introduce dislocations into their crystal. Things had reached a point where the most intuitive effort could not be neglected.

Soon the suggested idea took a very serious turn. If, indeed, a screw dislocation were formed within the growing crystal, a supporting step for migrating atoms would develop precisely on the surface. Even if the surface were covered with a layer of atoms, the step would survive, rather like the curb along the sidewalk under a layer of snow of its own height.

Suppressing the waiting period between layers, the new hypothesis allowed for a calculation entirely in accord with reality and implied, in addition, very precise configurations. In fact, as we have noted, the screw dislocation has a very definite point of emergence, thanks to its geometry. This point is anchored, and growth originating from the supporting step passing by this point can therefore only take place as a revolting spiral. Another sort of figure is imagined, one in which two neighboring dislocations operate jointly. Instead of an open spiral, the surface of the crystal will appear as covered with rising terraces, closed on themselves, with a repetitive mechanism functioning at the center.

At the time when Frank's schemas were proposed, no one recalled that exactly twenty years before two young scientists of Columbia University, Menzies and Sloat, had published pictures of magnificent macroscopic spirals observed on crystals of silicon carbide (a very hard matter used as an industrial abrasive) and had accompanied their photographs with this comment, typical of the philosophy of the man in the laboratory, who is typically an unwitting philosopher: "It can be seen that we are here in the presence of a perfectly definite fact. Generally our theories are quite clear, while the facts are much less so. Here the exact opposite is true."

Once again a premature experiment was waiting to be classified a posteriori. The screw dislocation was not born until around 1939, and its application to the mode of crystal growth was envisaged in 1949, while even the boldest physicists were quite reserved about the possibilities of experimental verification. And twenty years before the proof had been available!

And at the very moment when the theory of spiral growth was being communicated to an audience of specialists at the University of Bristol, a young scientist from London, skilled in microscopic examinations, offered at exactly the best chosen psychological moment an indisputable proof of spirals conforming in every way to Frank's schemas and discovered on the surface of beryl crystals. These spirals were a controversial subject because of their very perfection. Some, who had as they said "been observing spirals all their lives," did not readily accept the theory of dislocations, preferring that of swirling eddies of vapor near the crystal in formation. Others were disturbed to see appearing within the reach of the optical microscope a phenomenon whose source went back to interatomic distances. As a matter of fact, it was rather difficult to prove that the spirals observed could correspond to monoatomic steps. But subsequent experiments showed that, precisely as in the growth of the principal crystal, the foot of the spiral wall was a favored point of attraction for foreign atoms. So no sooner was it born than the spiral was underlined with various deposits, and its visibility was noticeably increased by an unforeseen decoration.

Besides this the steps of the spirals could be, in relation to the crystal structures and certain of their anomalies, of the height of a multiple of the elementary cell.

The important fact, in any case, was the passage from the unobservable, that is, from the individual behavior of atoms among themselves, to the macroscopic level. If the theory of dislocations had been valid only for an ensemble of ten or so neighboring atoms, its aesthetic character would have been preserved, but its applications very limited. On the other hand, if its consequences were such as to be manifest on the macroscopic scale, in observable dimensions, it would be of interest in regard not only to matter but also to materials.

Soon, too, spirals appeared in the field of the electron microscope in highly varied examples of crystallization, either more complicated or more simple than those rising from the formation of beryl.

At the present time, eight years after the first observations sanctioned by theory, a special column has been opened in scientific abstracts to which examples of crystal growths by this process are consigned. However, it must be clearly noted that this is but one of the modes of the formation of solids and that, if, for example, one studies the solidification of a metallic mass in fusion, other factors take precedence over the structural defect.

Another important observation to be made several years later was that one of the conditions for the observation of dislocations is that their density be relatively low. Thus, when in 1950–52 industry began to be interested in the single crystal (at any rate, in a very particular group of single crystals called "semiconductors"), the effort of geometric and chemical purification led to great progress concerning the observation of defects in arrangement.

Briefly it might be said that order and disorder are so intimately linked in matter that to varying degrees the pursuit of order, either in the framework of an intellectual aspiration for the generalization of the structural model or to fill a precise need such as that of the utilization of semiconducting properties, always causes a shock, or a knock, with a manifestation of disorder.

The utilization of the semiconductor is founded on a very particular distribution of electrons in materials of the same crystalline structure—the type of symmetry of the diamond. It involves, therefore, a question of properties—and of mathematical theories—more subtle than those concerned only with nuclei, the centers of gravity of their electronic environment. The result of the studies carried out by scientists of the Bell Telephone Company have led, thanks to the success of single crystals in which "harmful" impurities occur in the ratio of one atom in 10,000,000,000, to the application of mathematical physics to the technique of telecommunications. And this success won for those who effected it the Nobel Prize in physics for 1956, an unprecedented event which definitively removes the old frontiers, already very shaky, between pure and applied science.

From the point of view of our special interest, the single crystals of germanium—or of silicon—are of such a quality that these industrial materials are the matters most like the structural model. They still contain some dislocations, which may be uncovered by a chemical treatment of the surface and which are sufficiently widely spaced to appear under an optical microscope of rather low magnification.

Thus it was that in 1954 a stable arrangement of dislocations, forming a low-angle boundary between two regular fields without defects, actually appeared for the first time, while the schema of this boundary had been foreseen in 1939 by the Dutch physicist Burgers.

The year 1956 saw the most spectacular examples of proofs for the existence of dislocations. These proofs involved not only confirmation of their existence, including a distinction in certain crystals between the two types, edge and screw dislocations, but also of their movements. And the latter are produced exactly as shown by the soap-bubble model.

To grasp the movements of dislocations, it was necessary to make metal leaves so thin that, despite its weak penetrating power, the electron beam passes through them. Heidenreich had attempted this in America in 1948; Castaing succeeded in France in 1955, causing to appear on the screen segregated groups of atoms hardening aluminum in alloy with 4 per cent of copper (duralumin) by using ionic bombardment. In 1956 Bollmann, in Switzerland, pierced stainless steel, while, in Great Britain, Hirsch and his colleagues, using a German electronic microscope, succeeded in observing aluminum or stainless steel and, thanks to the inevitable heating of the sample, in stimulating the least stable arrangements of dislocations.

Once again the corresponding model, the one formed by the bubbles, was found by direct experiment to be valid, and once again nature not only answered in the affirmative but revealed even more than theory, once judged as too daring, had predicted.

The scientist is not seeking after triumphs. He gleans encouragement not only for himself but also for all those who, to varying degrees, as spectators, actors, or players of bit parts, participate in the same show. Even for those in the wings, a success on the stage is a powerful stimulant; a lighted projector—and to return to our first image—a pigeonhole which opens, a box which is properly furnished, is one more step toward new efforts which are well worth the trouble it takes to devote one's self to them.

So many problems still arise, both in the domain of matter and in the field of materials, that even the inspiriting steps we have rapidly sketched make no complete picture—but they do fill a few pigeonholes.

It is sometimes amazing to be brought face to face with problems which seem simple to one who is completely ignorant of them; the lesson can be a very useful one of its kind. In 1951 its erudite founder, Professor Bearzi, showed me in the Etruscan Museum in Florence those astonishing gold granulations with which the Etruscans decorated their jewels. No one, he said, had achieved such a performance limited by the rudimentary means available to these strange peoples, so despised by the haughty Romans. And the question had long been under study; patents had even been issued for a glue which was supposed to assure the adhesion of these microballs (they hardly exceed 0.1–0.2 mm. in diameter). But that procedure did not allow decoration of both sides of the plaque; it did not therefore duplicate that of the Etruscans, who had often produced double-faced jewels. Great experts studied the joinings of these granulations, some with a microscope, some with X-rays. Three years later, a Viennese artisan, moved by reproductions which he had seen of the granulations, tried to reproduce these objects which he had never handled. He did this in his room, with only the simplest of means at his disposal. And he made the joinings successfully with a natural solvent, showing that even in 1955 *Homo sapiens* could still lose the race and yield to *Homo faber*.

So there is still a place in our day for all artisans in the march of progress, from the most mathematical of physics to "do-it-yourself" soldering. But, whatever the manner of practicing the game, the rules must be applied, and the very import of the word "culture" is the making-known of these rules.

In a book in which his students hear the fine voice of their master, *De la méthode dans les sciences expérimentales*, the grand simplicity of a penetrating mind, Le Chatelier quotes Bacon: "In order to command nature, we must begin by obeying her laws." And as one sometimes hesitates between a small and a capital *t* when writing the word "truth" because even in physics there are small truths and large Truths, so there are also laws which are perhaps Laws.

Laboratory life is made up of many small facts: sums of positive results, compositions with negative results; and then one touches on something destined to grow—which may escape today only to reappear elsewhere tomorrow.

In ten years we have seen the spiral merging on beryl crystals, then on long-chained organic compounds, on gold spangles, on crystals of silicon carbide. And now, approaching matter no longer as an architect, but as an urbanist, crystallizing viruses like atoms, Wyckoff in the United States discovers organizations as regular as the models constructed for much less complex units. The electronic microscope shows many of these assemblages, with planes as perfect as rock cleavages. And yet at times, still somewhat in Limbo, a spiral appears to merge, seeming to animate living matter as it has awakened inert matter.