Violations of Symmetry in Physics

Of seven “mirrors” invented by physicists to describe the symmetry of the laws of nature, three have been shattered. Of those remaining, only one may still be wholly intact. It is called the CPT mirror

by Eugene P. Wigner

It was just nine years ago this month that physicists learned to their astonishment that left-handedness and right-handedness are built into the universe at the most fundamental level. Until December, 1956, they had assumed that if an event is possible, its mirror image is also possible, and that if one looks at some real event in a mirror, what one sees could also actually happen. This was known as reflection symmetry, and it forms the basis of the parity principle. In the summer of 1956 certain puzzling phenomena in nuclear physics led T. D. Lee and C. N. Yang to question the principle’s general validity. In a few months C. S. Wu, Ernest Ambler, Dale D. Hoppes and R. P. Hudson had demonstrated that the phenomena clearly violated the principle.

The parity principle was one of several symmetry principles that physicists had long accepted as axiomatic in developing their mathematical theories. With the fall of parity they became uneasy about the other principles and sought ways to test each of them in turn. As a result of this endeavor at least two more principles have fallen and a third has been called into serious question. This is time symmetry; the principle that nature is indifferent to the direction in which time flows. Physicists have believed deeply that nature is similar to an electric clock that will run forward or backward, depending on which way the starting knob is turned.

The various symmetries can be compared to mirrors that reflect natural events in carefully specified ways. The parity mirror, which we shall designate the $P$ mirror, is simply the ordinary mirror of everyday life. It has one property; however, that may puzzle the layman; accordingly we shall also let “$P$ mirror” stand for “physicists mirror” in order to distinguish it from the layman’s mirror, which we shall call the $L$ mirror.

Everyone is familiar with the fact that when an electric current flows in a coil of wire, it induces a magnetic field. We learned in school that the direction of the field—the direction of its north magnetic pole—can be determined by the “right-hand rule.” This rule states that if the forefinger of the right hand has the shape and direction of the current flow, the thumb of the right hand points to the north pole of the induced magnetic field.

The early students of electricity defined the direction of current flow as being from the positive terminal of a battery to the negative. Now that we understand that an electric current depends on the flow of electrons, it seems more reasonable to speak of the direction of electron flow, which is from the negative terminal to the positive. Therefore if we are told the direction in which electrons flow in a coil of wire, we must use a left-hand rule to determine the direction of north in the magnetic field. (We realize, of course, that “north” and “south” are themselves conventions based on the fact that a compass needle is said to point toward the earth’s North Pole.) In any case, in this article the direction of the magnetic field will be considered in relation to electron flow, which requires the left-hand rule. The reader is no doubt familiar with these elementary principles, but reviewing them may help to prevent confusion when we begin to look into mirrors.

Let us examine the parity mirror first. Imagine that we have before us on a table a coil of wire in which electrons are flowing clockwise as seen from above. The left-hand rule tells us that the induced magnetic field is pointing upward [see illustration on page 30]. Now imagine that there is a mirror on the ceiling directly over the table; what will we see in it? If we have placed our left hand next to the coil and shaped it to form the left-hand rule, we shall see in the mirror what appears to be a right hand with the thumb pointing down. The hand in the mirror tells us (correctly) that the electron flow as seen in the mirror is counterclockwise, but it also tells us (incorrectly) that the magnetic field is pointing down. The hand in the mirror misinforms us about the direction of the magnetic field because it (or appears to be) a right hand, and a real field is related to a real electron flow by a left hand. If we accept the right-hand (incorrect) view of the field direction, we can be said to be interpreting the mirror image as laymen; in this sense the mirror is an $L$ mirror. If, however, we insist as physicists that the electron flow is the prime reality and that the magnetic field is secondary, we will insist on using the left-hand rule to determine the direction of the magnetic field in the mirror and conclude that it is actually pointing back into the mirror and not out of the mirror. Thus the magnetic field on the tabletop and the field in the mirror—the physicist’s $P$ mirror—are pointing in the same direction [see illustration on page 31].

We can now describe the parity experiment performed by Miss Wu and her collaborators. In the center of a ring of electric current they placed some radioactive cobalt, which emits electrons and neutrinos when it decays. The whole experimental arrangement has a plane of symmetry: the plane through the ring current. There is nothing to distinguish the upward from the
downward direction. It nevertheless turned out that the electrons from the decaying cobalt atoms emerged asymmetrically: almost exclusively in the upward direction. If one were to place a mirror over the experiment, parallel to the plane of the ring current, the electrons would appear to be coming out of the mirror, or downward, which is not the direction they would travel if the current and radioactive material were real rather than mirror images [see illustration on pages 32 and 33].

This unexpected result attracted a great deal of attention—and a Nobel prize. The fact that the electrons emerged with a preferential direction, a direction that can be represented by the thumb of the left hand if the forefinger has the shape and direction of the electron flow, meant that the radioactivity of cobalt is partial toward the left hand.

If I may recall days long past, nobody was very happy with this result. It is a fact, of course, that most of us are as partial toward our right hand as cobalt is toward its left. We feel, however, that radioactive cobalt is not entitled to be partial because it should have forgotten its past and because, at the time it emitted the decay particles, it was under no influence that would have favored one side of the plane of the ring of current over the other. This plane was a symmetry plane at the beginning of the experiment; it should have remained a symmetry plane as long as it was undisturbed by outside influences. This statement is equivalent to the postulate that a possible sequence of real events should remain a possible sequence of events if every event is replaced by its mirror image. Evidently this is not the case for the disintegration process of radioactive cobalt.

Before long a score of physicists had independently proposed a reinterpretation of the Wu experiment that salvaged the principle of reflection symmetry. In essence they proposed that nature does not see itself in the P mirror but in a “magic mirror” where the signs of all electric charges are reversed. In this mirror the mirror image of an electron is a positron (a positive electron) and the mirror image of a radioactive cobalt nucleus is a similar nucleus made of antimatter (antineutrons and antiprotons). If one could view the Wu experiment in this proper mirror, one would see positrons flowing in the direction that electrons had been assumed to flow. Since a flow of positrons is equivalent to a flow of positive cur-

FALL OF TIME REVERSAL seems implied by an experiment showing that the $K^-\pi$ particle (also known as $K_s^0$) sometimes decays into two pi mesons ($\pi^+$ and $\pi^-$) instead of into three pi mesons, as required by $CP$ symmetry. If the $K^-\pi$ decays anywhere in the colored area there is a chance that the decay particles will pass through the two magnets and four spark chambers. The spark chambers are triggered to fire and thereby reveal particle tracks only if all four coincidence counters register the passage of a particle. The magnets produce a deflection (perpendicular to the plane of the page) that indicates the particle’s momentum. The experiment was performed at the Brookhaven National Laboratory by James H. Christenson, James W. Cronin, Vol L. Fitch and René Turlay of Princeton University.

K-PARTICLE-DECAY EXPERIMENT is being continued at Brookhaven National Laboratory by Cronin, Fitch and their associates, using the apparatus shown here. The motion picture camera atop the scaffold is used to record particle tracks in the spark chamber below it.
rent, one would have to use a right-hand rule to see how the magnetic field is pointing. One would then discover that the magnetic field is pointing out of the mirror, or downward, and thus directly opposite to the magnetic field in the real experiment. The decay particles emitted by the antimatter nuclei of radioactive cobalt would also tend to travel out of the mirror, or downward, thereby completing the mirror image of the Wu experiment [see illustration at right on page 33].

This reinterpretation of reflection symmetry was originally pure speculation, motivated solely by the desire to maintain the principle of reflection symmetry for the laws of nature. An experimental test was out of the question; even today we are far from being able to produce anticoal, that is, a cobalt nucleus consisting of antiprotons and antineutrons. It was possible, however, to test the new hypothesis in other ways. The reinterpretation turned out to be relevant and was in agreement with all experimental findings until quite recently. These findings include the direction of flight of particles emitted in decay reactions other than that of radioactive cobalt. In particular there is a case in which a radioactive particle as well as its antiparticle can be produced and observed. These particles are the muon and the antimuon; the decay of the antimuon looks in all details as the image of the decay of the muon would look in the magic mirror just described.

We have not yet mentioned the role of the ring current in Miss Wu's experiment. Its purpose is to create a magnetic field perpendicular to the plane of the current. This field in turn orients the spins of the nuclei of the radioactive cobalt atoms. The direction of the decay particles is related directly to the spins of the radioactive nuclei emitting them, and only indirectly by means of the magnetic field to the direction of the flow of electrons in the ring.

The spins of the cobalt nuclei carry an angular momentum, a fundamental property associated with rotation motion. In all studies of rotating motion before Miss Wu's experiment angular momentum was found to have a symmetry plane in the plane of rotation. If this plane were kept horizontal, one would expect the disintegration products (if any) of a rotating object to proceed with equal probability upward and downward. The fact that they do not when the rotating object happens to be a radioactive cobalt nucleus means that the total symmetry of the laws of nature is smaller than physicists had previously believed. The laws are not invariant if reflected in a P mirror. The magic mirror that gives a true reflection is called a CP mirror; it is a combination of the parity (P) mirror, which reflects the positions of particles, and a "charge conjugation" (C) mirror, which changes the sign of electric charges.

How many mirrors has the theoretician conceived all together? I hope that we will not be suspected of patent-preemption if we claim to have "invented" seven mirrors. They are essentially various composites of the P and C mirrors and a third mirror: the T mirror, which reflects the direction of time. The seven mirrors are P, C, T, CP, CT, PT and CPT.

We have already seen how electric currents and magnetic fields are reflected in the P mirror. Let us now consider how the P mirror reflects the path of a particle as it is scattered, or deflected, by another particle [see illustration on page 34]. We can imagine that the scatterer is a heavy particle, such as an oxygen nucleus, and that the incident particle is a light particle, for example a positron. Thus each particle has a positive electric charge (represented by a plus sign in the illustration). The positron is so light that it will hardly affect the position of the oxygen nucleus; we need be concerned only with the path of the positron as it approaches the oxygen nucleus and is scattered.

We must also take into account the fact that the incident particle has an angular momentum, or spin, and that the spin axis is parallel to the particle's direction of motion. After the particle has been scattered its direction of motion has changed, and the new direction of motion will be found to correlate with what has happened to the particle's spin angular momentum. If the spin remains pointing in the original direction (remains parallel), the particle's direction of motion will be somewhat above the plane of the original direction. If the spin flips around to point in the opposite direction (becomes antiparallel), the particle's direction of motion will be below the original plane. The particle can traverse either path and will take each path in a certain fraction of all cases observed.
The scattering event in front of the mirror will always be the same, but the image will be different in different mirrors. We shall assume that in each case the mirror is vertical and to the right, that is, between the object and the image. If the mirror is the physicist's P mirror, the reflected paths are just what one would expect. The path seen curving to the right in the actual case is seen curving to the left in the mirror. Moreover, the particle's direction of spin is reversed, so that if the particle seems to be spinning clockwise, as seen from the rear in the actual experiment, it will appear to be spinning counterclockwise as seen from the rear in the mirror image.

If one carried out this experiment, one would unquestionably find that the P mirror is right; with the accuracy of measurement now available one could not detect the difference between a real path and the path as it appears in the mirror. Yet we know from Miss Wu's experiment with radioactive cobalt that the mirror is not really right: in her experiment the P mirror gave an entirely incorrect picture. Hence we know that the P mirror is not quite right in general and that actuality will deviate from what it shows, even though in our scattering experiment its error would be immeasurably small.

Let us consider now how the scattering experiment looks in the C mirror [see top illustration on page 35]. The C mirror is not, of course, a material mirror: it does not change the location of points, the direction of motion or the sense of spin direction. All it does is substitute negative electric charges for positive electric charges and vice versa; or, more generally, it substitutes antimatter for matter and vice versa. Thus when we "look" into the C mirror we see that the oxygen nucleus of our scattering experiment is replaced by an antinucleus consisting of antineutrons and antiprotons, and so has an overall negative charge, and that the positron is replaced by an electron, which is also negatively charged.

The situation with the C mirror is quite similar to that with the P mirror. Since no one knows how to make an antimatter nucleus as heavy as the nucleus of oxygen, however, our particular scattering experiment cannot be performed. But it is known from similar scattering experiments with anti-particles that there are no observable differences between actual scattering patterns and their reflections in the C mirror. Nevertheless, it has been established by other experiments that C reflection is no more an exact symmetry than P reflection is. Unfortunately the experimental demonstration of C violation is not as direct as Miss Wu's demonstration of P violation. The argument for the violation of C symmetry is a mathematical one based on the observed spin direction of electrons and positrons that are respectively emitted by negative and positive muons. The experiment was performed in 1957 by G. Culligan, S. G. F. Frank, J. R. Holt, J. C. Kluyver and T. Massum of the University of Liverpool.

If the P and C mirrors are known to be slightly defective when they are tested individually, is it possible that the magic CP mirror mentioned earlier still provides a faithful reflection of reality? The CP image can be obtained in either of two ways: by reflecting the P image in a C mirror or by reflecting the C image in a P mirror. The fact that the image obtained by two such reflections is an excellent picture of reality follows from the fact that the image produced by each mirror is extremely close to reality if reality is reflected in it. Indeed, until recently physicists believed the slight discrepancies in the individual mirrors canceled each other, so that the CP mirror was in exact accord with reality. This certainly seemed to be the case, at least for a number of phenomena that occur in radioactive decays and that violate C and P separately. Before discussing the experiment that has now cast doubt on the CP mirror, I should make a few comments on the T mirror.

Like the C mirror, the T mirror does not change the paths of particles. It merely reverses their direction, thus implying that the time axis is reversed [see bottom illustration on page 35]. In fact the designation T stands for time-reversal symmetry. The concept is hard to accept intuitively because our everyday experience with events that are patently irreversible is so compelling; the pieces of a shattered teacup have never been known to reassemble themselves spontaneously. Irreversibility of this kind is not at issue. The physicist is concerned rather with the detailed reversibility of events at the atomic and subatomic scale. A model for this kind of irreversibility would be the behavior of
FALL OF PARITY, or reflection symmetry, followed the famous experiment performed in December, 1956, by C. S. Wu, Ernest Ambler and their collaborators. They placed a sample of radioactive cobalt in a magnetic field created by an electric coil and recorded the direction taken by one of the emerging decay products, namely electrons. According to the parity principle, the electrons should have emerged equally up and down; instead they emerged almost exclusively upward, in the direction of the magnetic field, as shown at the bottom in the diagram at left. If the experiment were reflected in the P mirror, the electrons would appear to emerge downward. If the radioactive cobalt and electric a perfectly elastic ball. If such a ball were dropped on a perfectly elastic surface, it would bounce forever. If one were to make a moving picture of this ball as it bounced, there would be no way to tell whether the film were being run forward or backward; the time axis would be completely reversible.

Until recently the T mirror, like the CP mirror, was believed to be exact. And for reasons I shall describe later, physicists are forced to believe that the combination of the T mirror with the CP mirror—the CPT mirror—may still remain exact, even though the C, P and T mirrors appear to fail separately.

Let us turn to the experiment that has cast doubt on the validity of the CP mirror and, by implication, on the validity of the T mirror. The experiment was carried out a little over a year ago at the Brookhaven National Laboratory by James H. Christenson, James W. Cronin, Val L. Fitch and René Turlay of Princeton University. One of the original purposes of the experiment was the confirmation of CP invariance, not a demonstration of its failure. Experiments occasionally give surprising results, however; this one certainly did. Nonetheless, the evidence for the violation of CP invariance is not as direct as the evidence for the violation of P invariance furnished by Miss Wu’s experiment or even the evidence for the violation of C invariance in the experiment of Culligan and his collaborators. The evidence for the failure of the CP mirror stems from one mode of decay exhibited by the K meson, or K particle. K particles are readily produced in a high-energy particle accelerator when a proton beam is directed at a suitable target, such as beryllium. The interaction of a high-energy proton with a neutron (contained in the atomic nuclei of the target) invariably yields two heavy particles, one of which is usually a proton or a neutron. When the bombardment energy is around 30 billion electron volts, as it was in the Brookhaven experiment, the other heavy particle is likely to be one of the so-called strange particles, such as a lambda particle or a sigma particle. Simultaneously the interaction produces a K particle, which can be either positive (K⁺), negative (K⁻) or neutral (K⁰).

The K meson is a very queer particle. It is the same particle whose puzzling decay behavior prompted Lee and Yang to question P invariance. Even before that it was ascertained that the K⁰ is not a single particle but two particles that are antiparticles of each other. When a particle has an electric charge, it can easily be separated from its antiparticle because the latter must have an oppo-
Current in the mirror were real, the electrons could actually go upward (middle diagram). Reflection symmetry had been disproved. The principle was salvaged by declaring that one sees itself in a “magic mirror,” or CP mirror, in which matter is replaced by antimatter. This symmetric relation is shown in the diagram at right, where radioactive cobalt is replaced by radioactive anticobalt and the electrons flowing in the coil are replaced by antielectrons, or positrons. The decay particles, also positrons, then emerge downward. The magnetic field is likewise reversed because a flow of positive charges gives rise to a magnetic field opposite in direction to that created by a flow of negative charges.

The existence of such superposition states is a consequence of the wave nature of matter. Similar superpositions also play an important role in the low-energy region, in particular in the theory of optically active organic compounds, such as optically active amino acids and sugars. For example, one form of sugar can have the property of rotating the plane of polarization of polarized light to the right. Another sugar of identical chemical composition will have the property of rotating the plane of polarized light to the left. The difference in optical activity is accounted for solely by the fact that the two compounds have three-dimensional structures that are mirror images and thus bear to each other the relation of left and right hands [see top illustration on page 36].

The quantum-mechanical interpretation of the position of an atom that determines whether an organic compound is left-handed or right-handed is plotted in the bottom illustration on page 36. The horizontal axis gives the position of the atom, in terms of left or right, in the optically active compound. The vertical axis is the “probability amplitude” for each position of the atom; the probability of finding the atom at any particular position is defined as the square of the probability amplitude. When the curve of the probability amplitude lies entirely to the right of the center, the atom is surely to the right, thereby creating an asymmetric situation. This corresponds to a right-handed, or dextro, compound. When the curve of probability amplitude lies entirely to the left, the atom is surely to the left, corresponding to the left-handed, or levo, compound.

The lower pair of curves in the illustration represents probability ampli-
P-mirror view of "scattering" is exactly what one would expect to see in an ordinary mirror. In the actual experiment (left) a positron is being scattered, or deflected, to the right as it approaches the positively charged nucleus of a fairly heavy atom, such as oxygen. The positron also possesses spin, or angular momentum, shown by the colored arrow. If the spin remains unchanged after scattering, the positron will be found above the plane of its original path; if the spin direction reverses, the positron will be found below the plane. In the mirror, as expected, all spins are opposite to those in the real experiment.

to CP reflection, should not be able to decay into a symmetric state, but it can decay into three pi mesons. A system of three pi mesons does have states that are antisymmetric with respect to CP. The three-pi decay is a slower process, hence the longer life of the $K^-_0$.

What Cronin, Fitch and their collaborators observed, however, is that a small fraction of the $K^-_0$ mesons do decay into two pi mesons, in defiance of CP symmetry. Since only about one in 500 of the $K^-_0$ mesons decays into two pi mesons, this mode of decay is more than 100,000 times slower for the $K^-_0$ than for the rapidly decaying $K^+_0$. Nevertheless, the "forbidden" decay does occur, and this is interpreted as a breakdown of CP symmetry.

One can see that the preceding argument is quite involved and is by no means so simple as that represented in the breakdown of P symmetry in Miss Wu’s experiment. As a result some physicists have been reluctant to accept the Cronin-Fitch experiment as conclusive evidence for the failure of CP symmetry. There may be a way out that preserves CP symmetry—in fact, several ways have been suggested—but the weight of the argument is increasing that CP has failed.

What follows from the violation of CP symmetry? Physicists are left with the belief that the very last mirror, the CPT mirror, is a true mirror. This belief is not based on nature’s innate preference for symmetry; it is based on the stubborn fact that we cannot formulate equations of motion in quantum field theory that lack this symmetry and still satisfy the postulates of Einstein’s special theory of relativity. If the principle of CPT symmetry is valid, it is evidence for the correctness of the general framework of quantum electrodynamics and of the special theory of relativity, not for nature’s preference for any additional symmetry.

It must be noted with some apprehension, however, that in order for the CPT mirror to remain valid the T mirror itself must be invalid. The reasoning, based on the Cronin-Fitch experiment, is this. The $K^-_0$ begins in an antisymmetric state and decays into a symmetric state when it is reflected in a CP mirror, thereby proving the mirror defective. If the image in the CP mirror is now reflected in the T mirror, the original asymmetry should be restored—provided that the CPT mirror (C plus P plus T) is valid. To turn a symmetric state into an antisymmetric one, however, the T mir-
ror by itself must produce an antisymmetric image. This is equivalent to saying that time is not invariant under reflection and that time-reversal symmetry has failed.

Physicists have scarcely begun to examine the implications of this final breakdown. Leaving aside the apparent collapse of $T$ symmetry, one can conclude from the failure of $P$, $C$ and $CP$ symmetry that the laws of nature do show a preference for either the right or the left hand. We are surrounded by many phenomena that appear to show just such a preference, or, more precisely, such a distinction between right and left. Most of us are right-handed and our hearts are on the left side. On a large scale we observe that the earth rotates to the left (counterclockwise) as seen from above the North Pole and proceeds to the left around the sun. The sun, in turn, travels to the right around the galaxy as viewed from above the north galactic pole. Heretofore these asymmetries were attributed to asymmetries in the initial conditions. Now it is possible to attribute the same asymmetries to the laws of motion, that is, to assume that the universe was initially more symmetrical than it is now and that the present state evolved as a result of the asymmetry of the laws of motion. Few people are as yet ready to accept these speculations; I personally do not believe they are valid. Such speculations could nevertheless be tested if we had enough information about the sense of rotation of planets in other solar systems.

The fact that the laws of nature have no pure space-reflection symmetry has one consequence that is unpleasant to admit. It deprives us of the illusion that these laws are—in perhaps a subtle but nonetheless a real sense—the simplest laws that can be conceived and that are compatible with some obvious experience. If one law of nature is possible, an alternative law obtained by reflecting the first law on a plane would be equally possible and equally simple. We had previously thought the law obtained by reflection would be identical with the original law, just as the reflection of a sphere is also a sphere. Now we know that this is not so. The difficulty began when Miss Wu's experiment showed us that the preferential direction of the decay particles of radioactive cobalt was arbitrarily upward. We got out of this difficulty by postulating another substance: radioactive anticobalt that emits particles downward. This restores

C-MIRROR VIEW OF SCATTERING is unlike that seen in any material mirror. The direction of particle paths and spin remains unchanged, but all charges are reversed.

T-MIRROR VIEW OF SCATTERING is also without resemblance to images seen in ordinary mirrors. In the T mirror the scattered particle travels the same path as in actuality, but proceeds in the opposite direction. The imaginary T mirror represents time-reversal.
MIRROR-IMAGE MOLECULES, called optical isomers, are well known in organic chemistry. This diagram shows two isomers of alanine, one of the 20 amino acids that living organisms use to build protein molecules. When placed in solution, the isomer at left, known as the levo form, rotates plane-polarized light to the left. Its mirror image, the dextro form, rotates polarized light to the right. Natural proteins are built exclusively from levo amino acids. Many other organic compounds occur in left-handed and right-handed configurations.

QUANTUM-MECHANICAL INTERPRETATION of dextro and levo organic compounds applies also to states of the neutral K meson. It invokes the concept of "probability amplitude," plotted as the vertical axis in these curves. The horizontal axis gives the position, in terms of left or right, of the atom that determines whether an organic compound is left- or right-handed. The probability of finding the atom at any particular position is the square of the probability amplitude. In the upper pair of curves the atom is surely either to the right or to the left. In the lower pair of curves the atom has an equal probability of being in the left or right position. How these curves apply to the K meson is explained in the text.

The symmetry because we can say that the laws of nature are symmetric but imply two kinds of substance, matter and antimatter. The apparent asymmetry in the laws of nature was thereby reduced to an asymmetry in the initial conditions that allowed matter to predominate over antimatter, at least in the only part of the universe we know at first hand.

The recent experiment of Cronin and Fitch indicates, however, that such an explanation is impossible. The indication, to be sure, is only indirect; we must explore all avenues that may yield another interpretation and preserve the spatial-reflection symmetry of the laws of nature. If these avenues do not lead out of the difficulty, we will have to admit that two absolutely equally simple laws of nature are conceivable, of which nature has chosen, in its grand arbitrariness, only one. The extent to which the laws of nature are the simplest conceivable laws has come to an end—no matter how subtly they may be formulated—as long as they are formulated in terms of concepts that are subject to the symmetry principles we are accustomed to associating with space-time.

The question naturally arises whether or not physics has experienced similar crises before. It has. In classical physics, matter was supposed to be infinitely subdivisible without change in its bulk properties such as specific gravity, viscosity or elasticity. The discovery of the atom put an end to this infinite subdivisibility. The atom therefore increased the complexity of the structure of matter, and this unavoidable new fact was for many people as obnoxious as the lack of reflection symmetry in the laws of nature is for us.

Most of the consequences of atomic structure that first appeared obnoxious were eliminated when physicists and chemists learned to use the atomic scale for their measurements and realized, for example, that atoms provide a natural unit of length. Without such a unit it would be difficult to understand why human beings have an average height somewhere between five and six feet; if all phenomena could be scaled up or down with impunity, men, mice and bacteria could be the same size. Atomic theory also provided explanations for the properties of matter, for its density, viscosity, elasticity and so on. Hence in its end result atomic theory enriched rather than complicated our picture of nature. There is hope, but as yet only a hope, that the present probing into the symmetry of space-time will have a similar result.