SCIENCE

VOL. LXXI — FRIDAY, JUNE 6, 1930 — No. 1849

SCIENCE: A Weekly Journal devoted to the Advancement of Science, edited by J. MCKEEN CATTELL and published every Friday by

THE SCIENCE PRESS
New York City: Grand Central Terminal
Lancaster, Pa. — Garrison, N. Y.
Annual Subscription, $6.00 — Single Copies, 15 Cts.

SCIENCE is the official organ of the American Association for the Advancement of Science. Information regarding membership in the Association may be secured from the office of the permanent secretary, in the Smithsonian Institution Building, Washington, D. C.

THE SYMMETRY OF TIME IN PHYSICS*

By Professor GILBERT N. LEWIS
UNIVERSITY OF CALIFORNIA

A FEW years ago I presented[1] the outline of a theory of light which required a radical change in our ideas of temporal causality. Instead of assuming the time-honored unidirectional causality, in which cause inevitably precedes effect, it proved necessary to assume that the present phenomena of a system are determined no more by the past states of the system than by its future states. Several recent developments in physics make this assumption seem less startling now than then; indeed I am fully convinced that there is no other way in which we can account for the known phenomena of light. Moreover, new discoveries in wave mechanics indicate that any conclusions concerning the emission of light must be extended to the emission of every kind of material particle.

By such considerations I was led, in "The Anatomy of Science," to examine with some care the meaning of time, as the word is used in physical science. It often happens that a common concept of daily life may profitably be simplified or refined when it is to be employed in a single branch of science. In studying the vastly complex phenomena of nature, as they come to us through our sense impressions, we could make little headway did we not segregate and idealize certain groups of like phenomena for the purpose of special study. Such segregations define the several branches of science, of which one of the most highly specialized and idealized is physics. Only a few types of phenomena are included within its bounds, and in its study we consciously abstain from employing many of our commonest ideas, such as purpose, goodness, beauty. In the physical sciences a statue of Praxiteles is a certain mass of crystalline calcium carbonate; the shape may or may not be mentioned. It was the scientific arrogance of a previous age that called a law of physics a law of nature. To speak so is to forget the bounds that we have ourselves established.

* Address given on the occasion of the presentation of the gold medal of the Society of Arts and Sciences, New York, April 17, 1930.

[1] Nature, 117: 236, 1926.

It is therefore evident that such notions as those of time and space may be given a simpler significance when we are dealing with a single science than when we are concerned with the complexities of natural occurrences in general. Our common idea of time is notably unidirectional, but this is largely due to the phenomena of consciousness and memory. Was Newton right in deliberately introducing into physics this common idea of the *flow* of time? Surely in one great branch of physics which we owe to his genius, the mechanics of conservative systems, it has long been recognized that there is need for nothing more than the simple idea of symmetrical time, which makes no distinction between past and future.

These two ideas of time, the unidirectional and the symmetrical, I have for brevity called "one-way" and "two-way" time. In going from the very simple science of mechanics to the very complex science of psychology, we must change from two-way to one-way time. It is important to inquire where this transition comes, and whether two-way time suffices for some parts of physics while one-way time is needed for the remainder.

The thesis that I announced earlier, and now wish to elaborate, is that throughout the sciences of physics and chemistry, symmetrical or two-way time everywhere suffices. As a philosophic speculation this view has received some attention, but I shall be much disappointed if it can not also be accepted as the statement of a law of physics, of exceptional scope and power, directly applicable to the solution of many classical and modern problems of physics.

Let us therefore review the several great branches of physics in the light of this thesis of symmetrical time. These branches are mechanics, thermodynamics, theory of radiation and electromagnetics. We shall see that nearly everywhere the physicist has purged from his science the use of one-way time, as though aware that this idea introduces an anthropomorphic element, alien to the ideals of physics. Nevertheless, in several important cases unidirectional time and unidirectional causality have been invoked, but always, as we shall proceed to show, in support of some false doctrine.

MECHANICS

Mechanics includes the still more limited science of kinematics. For a century or more there have been attempts,[2] culminating in the brilliant work of Minkowski, to make kinematics a branch of geometry. It was the hope, now fulfilled, that time could be combined with space into a four-dimensional manifold, of which the geometry should reproduce the science of kinematics.

[2] *E.g.*, Fechner (Kleine Schriften), "Der Raum hat vier Dimensionen."

To lighten the discussion, let us imagine one of these precursors of Minkowski, whom we may call Dr. X. In one of his note books we might read, "If this geometrical view of kinematics is correct there must be no distinction of past and future. It would be absurd in Euclidean geometry to prove a theorem by means of a diagram, and then to claim that the theorem becomes invalid if the diagram is turned upside down. Likewise there is no up or down in the four-dimensional geometry of kinematics."

It was also the belief of Dr. X that the rest of mechanics could in turn be identified with a still more comprehensive geometry, and it seemed to him that this view received some corroboration in the fact that the mechanics of conservative systems requires no dissymmetry of time. All the equations of mechanics are equally valid when t is replaced by $-t$. The chance of error is the same in calculating an eclipse of a thousand years ago or of a thousand years hence.

Becoming even bolder, this eager speculator hoped that not only mechanics but all physics might eventually be reduced to a geometry. He wrote, "If this belief be correct, Newton's idea of a flow of time has no place in physics. Until I see strong evidence to the contrary, I shall maintain this to be a basic law of physics, that all rules which are obtained from a study of physical processes hold with equal validity if these processes are reversed in time. Every equation and every explanation used in physics must be compatible with the symmetry of time. Thus we can no longer regard effect as subsequent to cause. If we think of the present as pushed into existence by the past, we must in precisely the same sense think of it as pulled into existence by the future."

THERMODYNAMICS

The second law of thermodynamics was a source of uneasiness to Dr. X. Recognizing the importance of its consequences, he still objected to the statement of Clausius, namely, that in any system left to itself the entropy increases steadily toward a maximum. This statement is in direct defiance to the law of the symmetry of time. Therefore to Dr. X it was a great satisfaction to read in a paper of Willard Gibbs that "the impossibility of an uncompensated decrease of entropy seems to be reduced to an improbability"; and later to follow the development of this thesis by Boltzmann until near the end of the famous lectures on "Gastheorie" he found Boltzmann saying, "Hence, for the universe, both directions of time are indistinguishable, as in space there is no up or down."

Boltzmann's qualifications of this statement seemed unnecessary to Dr. X, who now definitely included thermodynamics among those branches of physics which require symmetrical time only. In his note book we read, "The statistical interpretation of thermodynamics offered by Gibbs and Boltzmann affords for the first time an understanding of entropy. The process irreversible in time does not exist. This corollary of the law of symmetry in time itself leads to further important consequences. Thence we may prove to those who are still skeptical the atomic structure of matter, as follows: if we imagine two continuous media to diffuse into one another, such a diffusion would in principle be a phenomenon which by no physical means could be reversed, but if two streams composed of discrete particles should diffuse, then, although it might be a matter of great difficulty to recapture the particles and restore each to its own kind, yet in principle the process is reversible and indeed, according to Boltzmann, the separation will occur spontaneously if the system be left to itself for a sufficiently long period."

Dr. X adds a remark of much subtlety. "While we recognize the particulate nature of matter, we allow each particle to have a position and a velocity chosen from a whole continuum of possible values. Thus while we claim that an isolated system repeatedly returns nearly to its initial condition, we can not say that it returns exactly to that condition. If we start with a number of molecules all moving in precisely the same direction, we can not claim that after some disturbance they ever again move quite parallel to one another. This implies a sort of irreversibility, and while I am not sure that it is a contradiction to symmetrical time, I confess that I should be better satisfied if we could claim the exact recurrence of an initial state."

It is a pity that Dr. X did not live to see the universal acceptance of quantum theory, which assigns to an isolated system not an infinite continuum of states, but a finite number of discrete states. Thus every particular state exactly recurs within finite time. This modern picture is far simpler than that of Boltzmann, especially as we are going to see that each particular state occurs as often as every other. Hence molecular statistics furnishes quite elementary problems in the theory of probability, like the tossing of coins or the shuffling of cards.

In the main, however, the problems of thermodynamics to-day are not far different from those discussed by Boltzmann and Dr. X. In the note book of the latter we read, "The earth is constantly receiving energy from the sun, and in consequence water is continuously flowing over Niagara Falls, but these descriptive statements can not be called laws of physics. When we turn to the processes studied in the laboratory we find that when a hot and cold body are brought together, it is almost certain that the two temperatures will become equalized until no discernible difference remains. If we mix two mutually soluble liquids, we may expect the concentration to become nearly uniform. I have learned that it is possible to perform an operation upon the brains of mice so that they respond to no external stimuli, but can still run aimlessly about. If a large number of these mice are placed in one end of a box, that end is now heavier than the other; but this distinction rapidly disappears as the mice, in their random movements, cover with greater uniformity the bottom of the box, so that we may no longer discern any tendency of the box in one direction or the other. I claim that in all these cases there is no phenomenon irreversible in time, and indeed nothing more formidable occurs than in the proverbial case of a needle dropped into a haystack."

Before analyzing further these problems, we may consider a very interesting discussion of one-way time by Professor Eddington, in "The Nature of the Physical World." He arrives at a compromise, first by stating that one-way time does not occur in physics outside of thermodynamics, and then by reducing the principle of the increase of entropy from a "primary" to a "secondary" law, which does not prevent him, however, from deducing therefrom a "running down of the universe." To this compromise I can not agree. The first statement will be answered by the cases which will be discussed in the following sections, and the second can not be regarded as consistent with the new conception of thermodynamics.

We must be cautious about extending to the whole cosmos the rules which we have obtained from limited experiments in our small laboratories. The chance of obtaining valid results from such an extrapolation is very small, but it can be made in a purely formal way. If the universe is finite, as is now frequently supposed, then the formal application of our existing ideas of thermodynamics and statistics leads directly to the following statement: The precise present state of the universe has occurred in the past and will recur in the future, and in each case within finite time. Whether the universe actually is running down is, of course, another matter. All we can say is that such an assumption obtains no support from thermodynamics.

Let us, however, turn from the behavior of the universe, about which we know almost nothing, to the phenomena of the laboratory, about which we know a little more. Even in this limited domain it is going to be difficult enough to persuade ourselves that such a phenomenon as an explosion is wholly compatible with the thesis of symmetrical time. If a statement runs counter to a fixed habit of thought which has become nearly instinctive, it may be accepted by many, but believed by few. The use of one-way time has become second nature to us, and to oust from the mind all its implications, even when we set ourselves to do so, is no easy task. Nevertheless, perhaps we can make this task easier if we dig up by the roots and examine with all care this thing that we call an irreversible process.

We must begin by guarding against two human frailties—the feeling that there is some real distinction between familiar and unfamiliar things, and the fear of large numbers. Let us illustrate by means of a pack of cards, and at first a very small pack, say the ace, two, three and four of spades. There are twenty-four possible distributions, such as 1, 2, 3, 4; 4, 2, 1, 3; 4, 3, 2, 1, and so on. Of these the first and third are a little more easily described and remembered than the other twenty-two, which for this reason we call nondescript, but this is only a question of familiarity. A whist player would think of the arrangement, 1, 4, 3, 2, and there is no one of the twenty-four arrangements which might not be particularly significant in some other card game.

If our attention has been drawn to one particular distribution, we remark upon it when it results from random shuffling; but on the average each distribution, whether or not it has been favored by our attention, will turn up once in twenty-four times. If we now take a pack of fifty-two cards, the familiar, or easily described, distributions are relatively rare compared with all the nondescript arrangements, and if random shuffling should give the exact distribution of the pack as it comes from the manufacturer it would seem almost a miracle; yet we can say with the same certainty as before that any one particular distribution will, on the average, occur once in 52! times. The rules of arithmetic are the same for large numbers as for small.

There is no such thing as a well-shuffled pack, except with reference to certain familiar sequences. If the distribution does not closely resemble some familiar sequence, we might call it well shuffled. There is, however, another sense in which the idea of shuffling is of fundamental significance. If we examine a particular distribution and remember the sequence of the cards, afterwards the pack is said to be well shuffled when our remembrance of the previous distribution no longer aids us in guessing what a new distribution will be. This distinction between a known distribution and an entirely unknown one will prove to be fundamental in our study of the corresponding problems of thermodynamics.

Turning now to the irreversible thermodynamic process, we shall choose an illustration which is not quite so complicated as an explosion, but involves all essentials. A chemist has spent days in preparing a flask of nearly pure alcohol. This he places in a water bath, and then by accident the flask overturns and the alcohol diffuses through the water. His disappointment is in no way allayed by the fact that none of his material is really lost, nor by the belief that ultimately the molecules of alcohol will accidentally come together to give once more a nearly pure sample. That the chemist would be obliged to wait an unconscionable time for this chance restoration must be given no weight. If it occurred every ten minutes, the principle would be the same. It would still be necessary for him to devise rapid analytical methods to ascertain just when the fortunate event occurred. There is no question but that the accident has involved an element of *loss* which typifies the irreversible process (which is also spoken of as a process of dissipation, or degradation), but we shall see that this loss in no way implies a dissymmetry of time, nor indeed that it has any temporal implications whatever.

Without losing any of the characteristics of the reversible process, we may next examine one of the simplest of systems. Suppose that we have a cylinder closed at each end, and with a middle wall provided with a shutter. In this cylinder are one molecule each of three different gases, A, B and C, and the cylinder is in a thermostat at temperature T. In dealing with the individual molecules we are perhaps arrogating to ourselves the privileges of Maxwell's demon; but in recent years, if I may say so without offense, physicists have become demons.

Regarding each molecule, we shall ask only whether it is in the right or the left half of the cylinder. Obviously eight distributions are possible, such as A and B on the left and C on the right; or B on the left and A and C on the right. According to our ordinary assumptions, each of these distributions is equally probable, or, in other words, the system averages to be in each distribution one eighth of the time. Moreover, each of the eight distributions can be easily described and remembered, so that we are not troubled by a large number of nondescript states. Each distribution occurs over and over, but in no particular order, and in these occurrences there is no trace of dissymmetry with respect to time—there is no "running-down" process here.

Yet we may have a typical irreversible process. Suppose that the shutter is closed so as to trap a particular distribution, say all three molecules on the left. We become familiar with this one distribution and wish to study it further, but accidentally the shutter is opened, and instead of the one distribution, we have all eight succeeding one another in a random way. This is a complete analogy to the overturn of the flask of alcohol. If we desire once more to obtain and keep the one distribution in which all the molecules are on the left-hand side of the cylinder, we may exercise our prerogatives as Maxwell demons by closing the shutter from time to time and determining by spectroscopic means or otherwise which distribution is trapped. In about eight trials we shall obtain the desired result. Unless, however, there is in sentient beings the power to defy the second law of thermodynamics, we shall find that this method of obtaining the desired distribution requires at least as much work as the old-fashioned thermodynamical method of forcing the system into the particular distribution without the aid of demoniacal devices. This classical method consists in slowly pushing a piston from the extreme right of the cylinder as far as the middle wall. In this typical reversible process the work required to overcome the pressure of the three molecules is $3\ k\ T \ln 2 = k\ T \ln 8$. At the same time the entropy of the gas is diminished by $3\ k \ln 2$.

If we wish to obtain any other one of the particular distributions, from the general distribution, the same amount of work is required. Suppose the particular distribution desired is B on the left, A and C on the right. At the extreme left we have a piston permeable only to B, and at the extreme right a piston permeable only to A and C, and these pistons are moved slowly to the middle wall. We thus obtain the given distribution, and the sum of the work done upon the two pistons is $3\ k\ T \ln 2$. In every case, in passing from the general distribution to a particular known distribution, the gas loses entropy in the amount $3\ k \ln 2$. All these processes are completely reversible. If we start with any known distribution and let the proper pistons move outward from the center to the ends of the cylinder, we obtain the general distribution, the system does work in the amount $3\ k\ T \ln 2$, and the entropy of the gas increases by $3\ k \ln 2$.

The entropy of the general unknown distribution is greater than the entropy of any one known distribution by $3\ k \ln 2$. This, therefore, is the increase in entropy in the irreversible process which occurs when, after trapping any one *known* distribution, we open the shutter. It is evident, however, that the mere trapping of one distribution makes no change in the entropy, for the shutter may be made as frictionless as we please, and the mere act of opening or closing it will not change the entropy of the system. If we start with the shutter open, with all the eight distributions occurring one after another, and then close the shutter, the system is trapped in one distribution, but there is no change of entropy.

Whence we have now reached our most important conclusion. The increase in entropy comes when a *known* distribution goes over into an *unknown* distribution. The loss, which is characteristic of an irreversible process, is *loss of information.* In the simplest case, if we have one molecule which must be in one of two flasks, the entropy becomes less by $k \ln 2$, if we know which is the flask in which the molecule is trapped.

Gain in entropy always means loss of information, and nothing more. It is a subjective concept, but we can express it in its least subjective form, as follows. If, on a page, we read the description of a physico-chemical system, together with certain data which help to specify the system, the entropy of the system is determined by these specifications. If any of the essential data are erased, the entropy becomes greater; if any essential data are added, the entropy becomes less. Nothing further is needed to show that the irreversible process neither implies one-way time, nor has any other temporal implications. Time is not one of the variables of pure thermodynamics.

THE THEORY OF RADIATION

The laws of optics are entirely symmetrical with respect to the emission and absorption of light. The whole science of optics leaves nothing to be desired with respect to symmetry in time. When time is considered reversed, the emitting and absorbing objects merely exchange rôles, but the optical laws remain unchanged. On the other hand, the physical theories concerning the radiation from a particle, which were for a long time current, introduced the idea of one-way time in a notable manner. Let us quote once more from the note book of Dr. X.

"It has always been conceived that a particle which has been set in vibration, perhaps by collision with another particle, dissipates its energy in a continuous expanding spherical shell, every part of which moves steadily out into space until it meets an absorbing body. Since the energy all comes from the vibrational energy of one particle, the whole is regarded as a unitary process, although those parts of the shell of energy which meet neighboring objects may be absorbed within a very small fraction of a second, while other portions may travel years before they meet an absorbing object. The exact physical reversal of such a process is quite unthinkable. We should be obliged to imagine some prearrangement whereby each of a number of bodies far and near would, at the appropriate time and in the right direction, send out its quota of energy, all of which in the neighborhood of the absorbing particle would coalesce into a continuous spherical shell. As a rare event it might by chance occur that something approximating to this picture would be observed, but in no case could an exact reversal of the assumed process of radiation be found.

"The emission of a continuous spherical shell of energy is essentially irreversible in time, like the diffusion of continuous media which we have previously discussed. But we shall still be in trouble even if we assume that the energy radiating from a particle does not spread as a continuous shell, but goes to a limited number of other particles. Assume that a central particle emits energy to a number of other particles, and that its oscillations are damped as it loses energy, according to some simple law. The amounts of energy received by the several particles and the time of receipt are assumed to be causally connected, since the energy all flows from the one simply damped central atom.

"The exact temporal reverse either of this process or of this explanation is absurd. It would be necessary to imagine a central atom which receives energy from other atoms in such amounts and at such times as to increase continuously the oscillations of the central atom, according to a law exactly opposite to the law of damping; and we should be obliged to explain this phenomenon by saying that the amounts of energy emitted by the several particles, and the time of their emission, are all causally connected, by the fact that the energy is all to be received, and in a specified manner, by the central atom.

"After many considerations of this character I have come to the conclusion that the only process of radiation which can be harmonized with the symmetry of time is a process in which a single emitting particle at any one time sends its energy to only one receiving particle."

I think we may now agree that Dr. X was right and that if we are to assume the principle of symmetry in time, we are led irresistibly to a theory of radiation which has some of the characteristics of Einstein's theory of the light quantum. In particular we can not admit the possibility, now occasionally assumed, that in a single quantum process an atom may emit two photons to two separate atoms. Furthermore, in this theory of radiation we must assign to the emitting and to the absorbing atom equal and coordinate rôles with respect to the act of transmission of light, as I proposed in my former paper.

ELECTROMAGNETICS

Our friend Dr. X was eminently satisfied with the development of the theory of electricity and magnetism. He saw that the equations of Maxwell would be equally valid if time were reversed, and was therefore bewildered by Maxwell's deductions from these equations of a theory of radiation which, from his point of view, had all the faults of previous theories. How was it possible to obtain the old one-way theory of radiation from equations which involve nothing but symmetrical time? He did not see the full answer to this question until the development of the theory of *retarded potentials*. Then he realized that in the mathematical treatment of the problem two symmetrical solutions arose, of which one was arbitrarily discarded because it seemed inconsistent with common notions of causality.

In the whole history of physics this is the most remarkable example of the suppression by physicists of some of the consequences of their own equations, because they were not in accord with the old theory of unidirectional causality. We shall therefore attempt to analyze this problem, especially as this abstruse subject may be rendered quite simple by geometrical methods.

For this purpose Professor Wilson and I invented[3] the geometrical vector field. A vector field need not involve physical quantities such as momentum or force, but may be purely geometrical; for example, a line in space may serve to define any number of such vector fields. Thus we may, from every point in space, draw a vector along the perpendicular to the line, and with a magnitude proportional to the distance from the line.

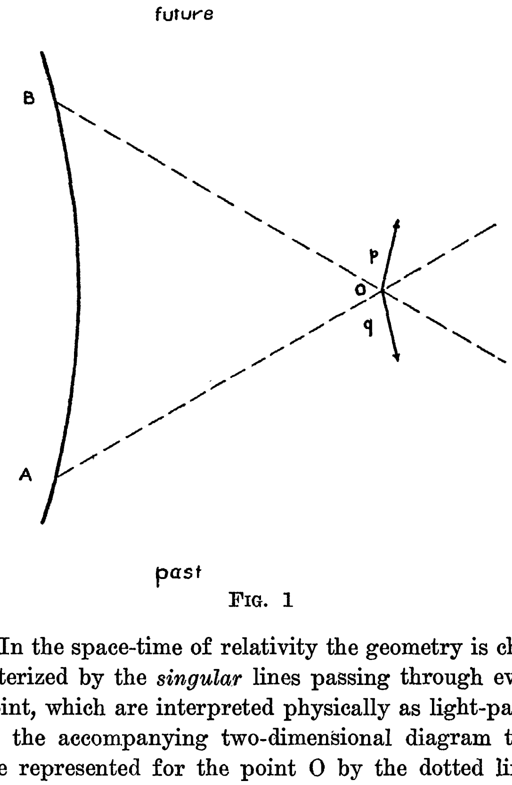

FIG. 1

In the space-time of relativity the geometry is characterized by the *singular* lines passing through every point, which are interpreted physically as light-paths. In the accompanying two-dimensional diagram they are represented for the point O by the dotted lines. In this geometry we set up the following vector field. Given any curve of the type AB, as the source of the field, then at any point O through which pass the singular lines OA and OB, the vector p is drawn

[3] *Proc. Amer. Acad.*, 48: 389, 1921.

upwards, parallel to the tangent of the curve at A, and with a magnitude which is the reciprocal of the distance from O to that tangent. The geometrical field thus set up has very remarkable properties. Our rules determine the variation of p in the neighborhood of O, and thus all its derivatives. The equations obtained are identical with all the complicated equations of the electromagnetic field produced by a moving and accelerated charge. This parallelism becomes an identity when we consider the curve AB as the locus in space-time of an electrical charge, and multiply the vector p by the magnitude of the charge. This vector, when projected upon a chosen time-axis, and upon the corresponding space, gives the scalar and the vector parts of the so-called retarded potential. It was so named because the influence of the charge at A was supposed to travel outward with the velocity of light and reach the point O at a later time.

Returning, however, to our geometry, we see that since there is no distinction between up and down, it is quite impossible to define the vector p without at the same time defining the vector q, which is drawn downward parallel to the curve at B. The projections of the vector q (multiplied by the charge) are quantities which have occasionally been studied under the name of *advanced potentials*. If they alone had been employed, the retarded potentials being discarded, we should have had an electromagnetic theory of light which would have been in equally good agreement with experimental facts, but in the interpretation of which we should have been obliged to regard the absorbing particle as the active agent, sucking in energy from all parts of space, in a spherical shell which contracts with the velocity of light.

As we now know, neither of these two electromagnetic theories is correct, and they can be used only as analogues; but in using such analogues we must hereafter give equal and symmetrical consideration to the retarded and to the advanced potentials; which means that in any theory of light we must consider the emitting and receiving agents as of coordinate importance. Thus, for example, if we wish to consider the probability that an atom X will emit a photon to an atom Y, and for this purpose imagine a virtual field produced by the particle X because of something analogous to its retarded potential, we must at the same time consider the particle Y as the seat of another virtual field of the advanced instead of the retarded type, and these two fields must be combined in a symmetrical manner to give the probability in question.

In recent months attempts have been made to extend quantum mechanics to the electromagnetic field, and here again the retarded potentials have been employed. We may safely predict that such attempts will not fully succeed until the retarded and advanced potentials are used simultaneously and symmetrically.

Applications to New Problems

We have seen that if science long ago had accepted the principle of symmetry in time, it would have eliminated the idea of unidirectional causality which has led to so many of the errors of classical physics. From this principle could have been deduced the atomic structure of matter and the newer thermodynamics. By its aid the flaws in the older theories of radiation and in the electromagnetic theory would have been seen. Moreover, the idea that light passes only from one particle to one particle, and that in this process the emitting and receiving atoms play coordinate parts, was directly derivable from the law of the symmetry of time. Let us now see whether there are new and unsettled problems which may be similarly solved.

Of the utmost importance to chemistry is the problem of reaction rates. Knowing only the state of equilibrium in a chemical reaction we know nothing of the rates of the individual reactions; but if we know the laws governing the rate of a reaction in both directions we may calculate the conditions of equilibrium. We now find that the complex problem of reaction rates may be reduced to the simpler problem of the transition probabilities between two elementary states. It will be a long time before many of these transition probabilities or intrinsic reaction rates can be calculated, but we shall see that there is one fundamental law that governs them.

When we say that we have chemical or thermal equilibrium, we mean that the average amount of each chemical substance (and also the number of particles of each species lying within a specified region, such as a region of energy), on the average remains constant. If, for example, substances A, B and C can change one into another the amount of each of these substances in equilibrium will not change, but thermodynamics alone tells us nothing of the paths by which they may go. For example, we might assume rapid processes from A to B, B to C and C to A, and slow processes for the reverse direction, A to C, C to B and B to A. There has, however, been a growing tendency to regard as impossible all such "cyclic equilibria." The principle was used in a limited way by Boltzmann, and was taken over in the quantum theory of the kinetics of gases. There was, however, a few years ago, a general disinclination to extend the principle to systems involving radiation. I believe I was the first to set up this principle[4] as a universal law in all physics and chemistry, applicable not only to chemical and physical proc-

[4] *Proc. Nat. Acad. Sci.*, 11: 179, 1925.

esses involving material substances, but also to processes involving light. I called it the principle of entire equilibrium. It has also been called the principle of microscopic reversibility and the principle of detailed balancing. It states that in equilibrium the rate of change along every detailed path is equal to the reverse rate.

Led to the formulation of this law by the idea of symmetry in time, which I was then beginning to develop, I remarked, "The law of entire equilibrium might have been called the law of reversibility to the last detail. If we should consider any one of the elementary processes which are occurring in a system at equilibrium, and could, let us say, obtain a moving-picture film for such a process, then this film reeled backward would present an equally accurate picture of a reverse process which is also occurring in the system and with equal frequency. Therefore in any system at equilibrium, time must lose the unidirectional character which plays so important a part in the development of the time concept. In a state of equilibrium there is no essential difference between backward and forward direction in time, or, in other words, there is complete symmetry with respect to past and future."

Indeed, we can readily see that any cyclic equilibrium would mean dissymmetry in time, for, suppose that in the case cited above we could say that the process occurring followed chiefly the route ABCAB . . . , then if time were reversed, we should obtain the opposite rule, namely that the main route would be ACBAC . . . .

Consider for any system the completely detailed quantum states designated as *a, b, c* . . . , the law of entire equilibrium states that the system changes from *a* to *b* as often as from *b* to *a*. Now the chance of a transition from *a* to *b* is proportional to the probability, p_a, of finding the system in *a* multiplied by an intrinsic probability, φ_{ab}, that when the system is in *a*, it will go over in a given time to *b*. The law of entire equilibrium therefore states that

$$p_a \varphi_{ab} = p_b \varphi_{ba} \tag{1}$$

Let us now examine these intrinsic probabilities, φ_{ab} and φ_{ba}. There seems at first sight nothing in the symmetry of time to restrict the values of these quantities. Supposing for the moment that these are the only two states, and assuming that, on the average, the system remains twice as long in the state *a* as in the state *b*, the same would be true if time were reversed. A moving-picture representing the successive changes would look the same if it were run in either direction. However, science can not rest content with such a statement regarding the intrinsic probabilities; it immediately inquires what physical quantities determine these probabilities.

According to the old idea of causality, the probability of a transition would be determined by the properties of the state which existed *before* the transition. In other words, the probability of the transition $a \rightarrow b$ would be some function of the properties of the state *a*, and the transition $b \rightarrow a$ would be the same function of the corresponding properties of the state *b*. Such a view is no longer permissible. If a transition depends upon the properties of the state preceding the transition, it must in equal measure depend upon the properties of the state following, so that φ_{ab} must be a symmetrical function of the properties of *a* and *b*. Since φ_{ba} must be taken as the same symmetrical function of the same properties, we obtain immediately the most fundamental law of physical and chemical processes,

$$\varphi_{ab} = \varphi_{ba} \tag{2}$$

This law stating the equality of direct and reverse transition probabilities has received no name, except in so far as it has occasionally been confused with the law stated in equation (1). We may call it the law of the mutuality of elementary processes, or, more simply, the mutuality principle. The name is intended to suggest the important fact that a transition in one direction and a transition in the opposite direction are not two physical entities, but one entity looked upon in two ways. Whatever we can say of one process, we can say of the other. We may think of a double arrow rather than of two arrows pointing in opposite directions. At present the law is best illustrated by some of the equations of quantum mechanics, such as the equations of Schrödinger in which transition probabilities are expressed as symmetrical functions of the "proper functions" of two states.

The law of mutuality holds for the elementary states, or, in other words, for the completely specified quantum states of a system. When a system is said to be in a condition which comprises a number of elementary states, the probability of a transition from one such condition to another depends not only upon the properties of the elementary states, but also upon their number. Thus, for example, if condition α comprises only one elementary state *a* and condition β comprises the two elementary states *b* and *c*, the probability of a transition $\alpha \rightarrow \beta$ is the sum of φ_{ab} and φ_{ba}, but if the system is in the condition β the probability of the reverse transition is not $\varphi_{ba} + \varphi_{ca}$ but is less, owing to the fact that when the system is in condition β it is in state *b* *or* state *c*, but not in both.

Generalizing, we may say that when we are dealing with a complicated chemical reaction in which a condition α goes into, or proceeds from, a condition β, and if we find that the specific reaction velocity is greater in the direction $\alpha \rightarrow \beta$ than in the direction $\beta \rightarrow \alpha$, it signifies that there are more elementary states comprised in the condition β than in the condition α.

By combining equations (1) and (2) we obtain a third law which is known as the equality of *a priori* probabilities and which, since it does not involve the element of time, we need discuss no further here. It is

$$p_a = p_b \qquad (3)$$

These three laws, of which, in fact, the first and third are both derivable from the second, are the fundamental laws of quantum kinetics and quantum statistics. They are at present the most important deductions from the law of the symmetry of time.

It is remarkable that so many positive conclusions result from the negative statement that physics requires no one-way time, but more important conclusions have been derived from the similar negative statements that we can not have a perpetual motion machine and that we can not determine absolute velocities. Whether the new law will be successful in leading to new and unexpected conclusions remains to be seen. At least, if accepted, it will warn us away from certain lines of thought which involve one-way time. There is at present in the study of quantum mechanics and in some interpretations of Heisenberg's uncertainty principle a tendency to introduce anew the idea of unidirectional causality. I feel convinced that this is a retrograde tendency which may introduce new errors into science.

OBITUARY

SHOSABURO WATASÉ

AMERICAN zoologists of the older generation well remember the young Japanese zoologist who came to America in 1886, became Bruce Fellow in Zoology at the Johns Hopkins University, where he took his Ph.D. degree in 1890, and was successively attached to Whitman's Department in Clark University (1890–1892) and the University of Chicago (1892–1899) before his return to Japan. He was also a well-known figure at Woods Hole where he spent most of his summers in America from 1888 on. Few of the many Japanese who have begun their scientific careers in America identified themselves more closely with the country of their residence, attained such sympathetic and thorough understanding of its history and spirit, so loved its literature and that of old England, or obtained such mastery of its spoken and written language as Sho Watasé. His friends had ceased to regard him as foreign, and thought of him as a permanent acquisition, so apparently domiciled was he in American social and academic life, until his sudden decision to return to Japan and accept the chair of zoology in the University of Tokyo in 1899.

This was a total loss to American zoology, for he resumed the old way of his life as completely as he had abandoned it for over twelve years, and his only visits to America thereafter were two brief ones on scientific missions. His return to Japan cut short a line of work in which he had already obtained marked distinction, and thereafter the needs of Tokyo and Japan claimed his undivided allegiance. This little sketch of his life will serve to fill out the picture for those who knew him, and to shadow forth a notable life to those who did not have this privilege.

Watasé was born in Tokyo, November, 1862, and there also he died March 8, 1929. He came first under the influence of American educational ideas when at the age of seventeen he entered Sapporo Agricultural College, an institution organized by William Smith Clark, President of the Massachusetts Agricultural College, under a special grant of the Japanese Government in 1875. Among the members of his class (1884) were the geographer Jugo Shiga, the journalist Gentei Zumoto and the statesman Tetsuji Hayakawa. From 1884 to 1886 he studied zoology at the University of Tokyo under Mitsukuri; from 1886 to 1890 he studied with William Keith Brooks at the Johns Hopkins University, held the Bruce Fellowship and received his Ph.D. degree there in 1890. Among his fellow students there were—E. G. Conklin, T. H. Morgan and E. A. Andrews. Then followed his years at Clark University, at Woods Hole and at the University of Chicago with C. O. Whitman, until his return to the University of Tokyo in 1899. From this institution he received the degree of D.Sc. in 1899, and succeeded Mitsukuri as head of the zoological department there in 1901.

He returned to America in 1907 as Japanese delegate to the International Zoological Congress held in Boston. On his return to Japan he took with him bullfrogs, which have become established in Japan and are very generally cultivated there as an article of food. Again on a trip to India in 1909–1910 he brought back the mongoose and established it in Japan on the Okinawa Islands, where it has almost exterminated venomous snakes which formerly caused serious loss of life. In 1922 on the occasion of another trip to the United States and Canada he inves-