

The Logic of Modern Physics *

P. W. BRIDGMAN

WHATEVER MAY BE one's opinion as to our permanent acceptance of the analytical details of Einstein's restricted and general theories of relativity, there can be no doubt that through these theories physics is permanently changed. It was a great shock to discover that classical concepts, accepted unquestioningly, were inadequate to meet the actual situation, and the shock of this discovery has resulted in a critical attitude toward our whole conceptual structure which must at least in part be permanent. Reflection on the situation after the event shows that it should not have needed the new experimental facts which led to relativity to convince us of the inadequacy of our previous concepts, but that a sufficiently shrewd analysis should have prepared us for at least the possibility of what Einstein did.

Looking now to the future, our ideas of what external nature is will always be subject to change as we gain new experimental knowledge, but there is a part of our attitude to nature which should not be subject to future change, namely that part which rests on the permanent basis of the character of our minds. It is precisely here, in an improved understanding of our mental relations to nature, that the permanent contribution of relativity is to be found. We should now make it our business to understand so thoroughly the character of our permanent mental relations to nature that another change in our attitude, such as that due to Einstein, shall be forever impossible. It was perhaps excusable that a revolution in mental attitude should occur once, because after all physics is a young science, and physicists have been very busy, but it would certainly be a reproach if such a revolution should ever prove necessary again.

NEW KINDS OF EXPERIENCE ALWAYS POSSIBLE

The first lesson of our recent experience with relativity is merely an intensification and emphasis of the lesson which all past experience has also taught, namely, that when experiment is pushed into new domains, we must be prepared for new facts, of an entirely different character from

* Reprinted by kind permission of the author and the publisher from P. W. Bridgman, *The Logic of Modern Physics*, pp. 1-25. The Macmillan Company, copyright 1928.

those of our former experience. This is taught not only by the discovery of those unsuspected properties of matter moving with high velocities, which inspired the theory of relativity, but also even more emphatically by the new facts in the quantum domain. To a certain extent, of course, the recognition of all this does not involve a change of former attitude; the *fact* has always been for the physicist the one ultimate thing from which there is no appeal, and in the face of which the only possible attitude is a humility almost religious. The new feature in the present situation is an intensified conviction that in reality new orders of experience do exist, and that we may expect to meet them continually. We have already encountered new phenomena in going to high velocities, and in going to small scales of magnitude: we may similarly expect to find them, for example, in dealing with relations of cosmic magnitudes, or in dealing with the properties of matter of enormous densities, such as is supposed to exist in the stars.

Implied in this recognition of the possibility of new experience beyond our present range, is the recognition that no element of a physical situation, no matter how apparently irrelevant or trivial, may be dismissed as without effect on the final result until proved to be without effect by actual experiment.

The attitude of the physicist must therefore be one of pure empiricism. He recognizes no *a priori* principles which determine or limit the possibilities of new experience. Experience is determined only by experience. This practically means that we must give up the demand that all nature be embraced in any formula, either simple or complicated. It may perhaps turn out eventually that as a matter of fact nature can be embraced in a formula, but we must so organize our thinking as not to demand it as a necessity.

THE OPERATIONAL CHARACTER OF CONCEPTS

Einstein's Contribution in Changing Our Attitude Toward Concepts

Recognizing the essential unpredictability of experiment beyond our present range, the physicist, if he is to escape continually revising his attitude, must use in describing and correlating nature concepts of such a character that our present experience does not exact hostages of the future. Now here it seems to me is the greatest contribution of Einstein. Although he himself does not explicitly state or emphasize it, I believe that a study of what he has done will show that he has essentially modified our view of what the concepts useful in physics are and should be. Hitherto many of the concepts of physics have been defined in terms of their properties. An excellent example is afforded by Newton's concept of absolute time. The following quotation from the Scholium in Book I of the *Principia* is illuminating:

I do not define Time, Space, Place or Motion, as being well known to all. Only I must observe that the vulgar conceive those quantities under no other notions but from the relation they bear to sensible objects. And thence arise

certain prejudices, for the removing of which, it will be convenient to distinguish them into Absolute and Relative, True and Apparent, Mathematical and Common.

(1) Absolute, True, and Mathematical Time, of itself, and from its own nature flows equably without regard to anything external, and by another name is called Duration.

Now there is no assurance whatever that there exists in nature anything with properties like those assumed in the definition, and physics, when reduced to concepts of this character, becomes as purely an abstract science and as far removed from reality as the abstract geometry of the mathematicians, built on postulates. It is a task for experiment to discover whether concepts so defined correspond to anything in nature, and we must always be prepared to find that the concepts correspond to nothing or only partially correspond. In particular, if we examine the definition of absolute time in the light of experiment, we find nothing in nature with such properties.

The new attitude toward a concept is entirely different. We may illustrate by considering the concept of length: what do we mean by the length of an object? We evidently know what we mean by length if we can tell what the length of any and every object is, and for the physicist nothing more is required. To find the length of an object, we have to perform certain physical operations. The concept of length is therefore fixed when the operations by which length is measured are fixed: that is, the concept of length involves as much as and nothing more than the set of operations by which length is determined. In general, we mean by any concept nothing more than a set of operations; *the concept is synonymous with the corresponding set of operations*. If the concept is physical, as of length, the operations are actual physical operations, namely, those by which length is measured; or if the concept is mental, as of mathematical continuity, the operations are mental operations, namely those by which we determine whether a given aggregate of magnitudes is continuous. It is not intended to imply that there is a hard and fast division between physical and mental concepts, or that one kind of concept does not always contain an element of the other; this classification of concept is not important for our future considerations.

We must demand that the set of operations equivalent to any concept be a unique set, for otherwise there are possibilities of ambiguity in practical applications which we cannot admit.

Applying this idea of "concept" to absolute time, we do not understand the meaning of absolute time unless we can tell how to determine the absolute time of any concrete event, *i.e.*, unless we can measure absolute time. Now we merely have to examine any of the possible operations by which we measure time to see that all such operations are relative operations. Therefore the previous statement that absolute time does not exist is replaced by the statement that absolute time is meaningless. And in

making this statement we are not saying something new about nature, but are merely bringing to light implications already contained in the physical operations used in measuring time.

It is evident that if we adopt this point of view toward concepts, namely that the proper definition of a concept is not in terms of its properties but in terms of actual operations, we need run no danger of having to revise our attitude toward nature. For if experience is always described in terms of experience, there must always be correspondence between experience and our description of it, and we need never be embarrassed, as we were in attempting to find in nature the prototype of Newton's absolute time. Furthermore, if we remember that the operations to which a physical concept are equivalent are actual physical operations, the concepts can be defined only in the range of actual experiment, and are undefined and meaningless in regions as yet untouched by experiment. It follows that strictly speaking we cannot make statements at all about regions as yet untouched, and that when we do make such statements, as we inevitably shall, we are making a conventionalized extrapolation, of the looseness of which we must be fully conscious, and the justification of which is in the experiment of the future.

There probably is no statement either in Einstein or other writers that the change described above in the use of "concept" has been self-consciously made, but that such is the case is proved, I believe, by an examination of the way concepts are now handled by Einstein and others. For of course the true meaning of a term is to be found by observing what a man does with it, not by what he says about it. We may show that this is the actual sense in which "concept" is coming to be used by examining in particular Einstein's treatment of simultaneity.

Before Einstein, the concept of simultaneity was defined in terms of properties. It was a property of two events, when described with respect to their relation in time, that one event was either before the other, or after it, or simultaneous with it. Simultaneity was a property of the two events alone and nothing else; either two events were simultaneous or they were not. The justification for using this term in this way was that it seemed to describe the behavior of actual things. But of course experience then was restricted to a narrow range. When the range of experience was broadened, as by going to high velocities, it was found that the concepts no longer applied, because there was no counterpart in experience for this absolute relation between two events. Einstein now subjected the concept of simultaneity to a critique, which consisted essentially in showing that the operations which enable two events to be described as simultaneous involve measurements on the two events made by an observer, so that "simultaneity" is, therefore, not an absolute property of the two events and nothing else, but must also involve the relation of the events to the observer. Until therefore we have experimental proof to the contrary, we must be prepared to find that the simultaneity of two events depends

on their relation to the observer, and in particular on their velocity. Einstein, in thus analyzing what is involved in making a judgment of simultaneity, and in seizing on the act of the observer as the essence of the situation, is actually adopting a new point of view as to what the concepts of physics should be, namely, the operational view.

Of course Einstein actually went much further than this, and found precisely how the operations for judging simultaneity change when the observer moves, and obtained quantitative expressions for the effect of the motion of the observer on the relative time of two events. We may notice, parenthetically, that there is much freedom of choice in selecting the exact operations; those which Einstein chose were determined by convenience and simplicity with relation to light beams. Entirely apart from the precise quantitative relations of Einstein's theory, however, the important point for us is that if we had adopted the operational point of view, we would, before the discovery of the actual physical facts, have seen that simultaneity is essentially a relative concept, and would have left room in our thinking for the discovery of such effects as were later found.

Detailed Discussion of the Concept of Length

We may now gain further familiarity with the operational attitude toward a concept and some of its implications by examining from this point of view the concept of length. Our task is to find the operations by which we measure the length of any concrete physical object. We begin with objects of our commonest experience, such as a house or a house lot. What we do is sufficiently indicated by the following rough description. We start with a measuring rod, lay it on the object so that one of its ends coincides with one end of the object, mark on the object the position of the other end of the rod, then move the rod along in a straight line extension of its previous position until the first end coincides with the previous position of the second end, repeat this process as often as we can, and call the length the total number of times the rod was applied. This procedure, apparently so simple, is in practice exceedingly complicated, and doubtless a full description of all the precautions that must be taken would fill a large treatise. We must, for example, be sure that the temperature of the rod is the standard temperature at which its length is defined, or else we must make a correction for it; or we must correct for the gravitational distortion of the rod if we measure a vertical length; or we must be sure that the rod is not a magnet or is not subject to electrical forces. All these precautions would occur to every physicist. But we must also go further and specify all the details by which the rod is moved from one position to the next on the object—its precise path through space and its velocity and acceleration in getting from one position to another. Practically of course, precautions such as these are not mentioned, but the justification

is in our experience that variations of procedure of this kind are without effect on the final result. But we always have to recognize that all our experience is subject to error, and that at some time in the future we may have to specify more carefully the acceleration, for example, of the rod in moving from one position to another, if experimental accuracy should be so increased as to show a measurable effect. In *principle* the operations by which length is measured should be *uniquely* specified. If we have more than one set of operations, we have more than one concept, and strictly there should be a separate name to correspond to each different set of operations.

So much for the length of a stationary object, which is complicated enough. Now suppose we have to measure a moving street car. The simplest, and what we may call the "naïve" procedure, is to board the car with our meter stick and repeat the operations we would apply to a stationary body. Notice that this procedure reduces to that already adopted in the limiting case when the velocity of the street car vanishes. But here there may be new questions of detail. How shall we jump on to the car with our stick in hand? Shall we run and jump on from behind, or shall we let it pick us up from in front? Or perhaps does now the material of which the stick is composed make a difference, although previously it did not? All these questions must be answered by experiment. We believe from present evidence that it makes no difference how we jump on to the car, or of what material the rod is made, and that the length of the car found in this way will be the same as if it were at rest. But the experiments are more difficult, and we are not so sure of our conclusions as before. Now there are very obvious limitations to the procedure just given. If the street car is going too fast, we can not board it directly, but must use devices, such as getting on from a moving automobile; and, more important still, there are limitations to the velocity that can be given to street cars or to meter sticks by any practical means in our control, so that the moving bodies which can be measured in this way are restricted to a low range of velocity. If we want to be able to measure the length of bodies moving with higher velocities such as we find existing in nature (stars or cathode particles), we must adopt another definition and other operations for measuring length, which also reduce to the operations already adopted in the static case. This is precisely what Einstein did. Since Einstein's operations were different from our operations above, his "*length*" does not mean the same as our "*length*." We must accordingly be prepared to find that the length of a moving body measured by the procedure of Einstein is not the same as that above; this of course is the fact, and the transformation formulas of relativity give the precise connection between the two lengths.

Einstein's procedure for measuring the length of bodies in motion was dictated not only by the consideration that it must be applicable to bodies with high velocities, but also by mathematical convenience, in that Ein-