The World Philosophy Made

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Imprint Princeton University Press, 2019

ISBN 9780691197418

Permalink https://books.scholarsportal.info/uri/ebooks/ebooks6/degruyter6/2020-08-10/1/9780691197418

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CHAPTER 10

PHILOSOPHY AND PHYSICS

The continuity of physical categories over centuries; the collaboration of philosophically minded physicists with philosophers trained in physics; Einstein on the importance of philosophy; the key question: What do the unobservable parts of physical theories tell us about the universe?; the eighteenth-century debate over absolute space and the nineteenth-century statement of Newtonian theory without it; the abandonment of absolute time in special relativity; light, gravity, and general relativity; puzzles and interpretations of quantum mechanics.

Physics is our most fundamental science. Its task is to explain what the universe is like, including when, how, and why macro- and microscopic events happen as they do. Much of this task requires elucidating the central notions needed for such explanations—time, space, matter, and motion. These were central to the physics of Aristotle, which remained dominant until the sixteenth century. They remained central, with important modifications, in Newton's *Principia Mathematica* at the end of the seventeenth century. By the early twentieth century, they were still central, despite being radically rethought.

The philosophy of physics is about physics; it attempts to explain what physics tells us. That may sound strange. Why do we need a separate study to explain what another study says? The question, though a good one, is somewhat misguided. The philosophy of physics is not an area of study distinct from physics. It is a philosophically self-conscious way of doing physics itself. In one way or another, this has always been so. Recall the first sentence of Aristotle's metaphysics, "All men by nature desire to know." Among the things *Homo sapiens* have always most wanted to know is what the vast universe, of which we are such seemingly insignificant inhabitants, is really like, including what it was like before we were here, and will be like after we are gone.

Nearly 2400 years ago Aristotle systematized his thoughts on the subject in his *Physics.* He was followed centuries later by such men as Roger Bacon in the thirteenth century, William of Ockham, John Buridan, and Nicholas Oresme in the fourteenth century, Nicolaus Copernicus, Johannes Kepler, Galileo Galilei, and René Descartes in the sixteenth and seventeenth, and, of course, Isaac Newton in the late seventeenth and early eighteenth century. Some of these men were monks or theologians, some were mathematicians, some were astute observers or experimentalists, and some were all three. But, whatever else they were, all were, in part, philosophers, as the title of Newton's great work, *Philosophiae Naturalis Principia Mathematica,* reminds us. The same is true of Albert Einstein (1879–1955) and several other great physicists of our era. Hence the original name of the subject, *natural philosophy,* still fits.

There are of course very significant differences between professionals whose primary appointments today are in physics labs or departments and those whose primary appointments are in philosophy departments. But this doesn't erase the overlap between philosophically minded physicists and scientifically informed philosophers of physics. The philosophers use tools of conceptual clarification and rigorous evaluation of arguments to reveal potential flaws and presuppositions of important scientific reasoning that, if left unaddressed, may cloud our understanding of physical theories and inhibit their further development. That is why today's philosophers of physics are typically trained philosophers who are also physicists, and why some of the greatest physicists, like Einstein, were self-consciously philosophically minded.

Einstein himself always recognized this. Writing in his autobiography about the importance of his philosophical studies, he says:

> Today everyone knows, of course, that all attempts to clarify this paradox [involving the nature of light that lead to special relativity] satisfactorily were condemned to failure as long as the axiom of the absolute character of time, or of simultaneity, was rooted unrecognized in the unconscious. To recognize clearly this axiom and its arbitrary character already implies the essentials of the solution of the problem. The type of critical reasoning required for the discovery of this central point was decisively furthered, in my case, especially by the reading of David Hume's and Ernst Mach's philosophical writings.[1]

Much earlier, in 1915, Einstein had written something similar in a letter to the scientifically educated philosopher and founder of logical positivism, Moritz Schlick.

> Berlin, 14 December 1915
>
> I received your paper yesterday, and have studied it thoroughly. It's among the best yet of what's been written about relativity. Nothing nearly as clear has previously been written about its philosophical aspects. At the same time you have full command of the theory itself. . . . Truly masterful is your discussion of relativity theory's relationship to the philosophy of Kant and his

> disciples. Their trust in the "incontrovertible certainty" of "a priori synthetic judgments" is badly shaken by the recognition that even a single one of those judgments is invalid. Your exposition is also quite right that positivism suggested relativity theory, without requiring it. Also you have correctly seen that this line of thought was of great influence on my efforts and indeed Mach and still much more Hume, whose Treatise on Human Nature I studied with eagerness and admiration shortly before finding relativity theory.[2]

What Einstein learned from Hume and Mach was not anything specifically about space, time, or motion (though both had many ideas about them, and Hume held that there is no notion of time separate from the motion of bodies). Rather, what Einstein found illuminating was a gap these thinkers made vivid to him—the gap between our habitual ways of thinking, directly but often uncritically derived from sense experience, and the proper concepts needed to truly describe reality. Einstein's debt to these philosophers was not to the contents of their doctrines, but to the inspiration provided by their willingness to rethink and revise even our most basic—seemingly rock-solid—commonsense notions, if doing so would increase our knowledge.[3]

In Einstein's case, the notions to be revised involved our pre-theoretic conceptions of space, time, and simultaneity. What the philosopher in him realized was that no matter how great their everyday utility to us, and no matter how deeply embedded they are in our biologically determined perceptual and cognitive architecture, there is no guarantee that these ordinary notions are well suited to understanding the fundamental structure of the universe. What the great scientist in him realized was that the universe *was* telling us that these notions had to be revised. It is a tribute to his genius that he saw how to do it.

The relationship between *physics* and *philosophy of physics* today is, if anything, closer than it was in Einstein's day. One can get a sense of why this should be so by thinking of physical theories as collections of abstract, mathematically sophisticated representations of reality which, when combined with attested observations, allow us to predict further observable events. When these events occur, the theory is partially confirmed (though not conclusively proved); when they don't occur, it is often necessary to modify the theory that led to false predictions. This way of thinking of theories—as prediction-generating representations of reality—raises three natural questions. Which aspects of the theoretical representation of reality are merely conventional devices adopted to smooth the calculations needed to make observational predictions? Which aspects of the theory are genuinely representational, and so make claims (beyond the directly observable) about the nature of reality? What (beyond the directly observable) do our best physical theories tell us about reality?

One view, formerly far more popular than it is today, dismissed the second and third of these questions by taking theoretical claims about non-observational matters to be mere calculating devices, with no representational content beyond the observational predictions to which they contribute. In the decades since this view has fallen from favor, philosophers of physics and philosophically minded physicists have struggled to answer questions about what our physical theories are telling us about the universe. Physicists themselves differ in the degree to which they are engaged in this enterprise. Some are understandably more concerned with using physical theories to calculate precise solutions to clear empirically stateable problems, while others place an equal priority on conceptualizing what, exactly, the non-directly verifiable aspects of their theories tell us about the world. These are the physicists who interact most deeply with today's philosophers of physics—not, of course, by looking to philosophers for new physical theories, but by working with philosophers of physics to clarify what their own physical theories are telling us (which in turn may spark further improvements).

To illustrate this, I will return for a moment to Newton. In chapter 3 we saw that he accepted absolute space and time in part because it was deeply intuitive and in part because stating physical laws in terms of them allowed him to explain the otherwise puzzling observed behavior of water in a spinning bucket. Thus absolute space and time were not empirically gratuitous constructs. They did, however, give him more structure than he needed, and so generated further puzzles. In Newton's 3-D Euclidean space, a distribution of matter in one portion of absolute space could (in principle) be relocated in a straight line to another location, preserving all relative spatial positions and sizes, without having any effect on the laws of physics. So the question *Where are we in absolute space?* seems to be inherently impossible to answer; similarly for questions about absolute velocities.

Newton realized this. He recognized that as long as we don't introduce new circular motions (like the spinning bucket), or eliminate such motions in the initial state, we can imagine the entire collection of matter moving in a straight line in one direction at a constant speed without changing any of the physical relationships between any of the bodies. This is puzzling because it suggests that no empirical evidence could be brought to bear on the question of which of these states our universe is in.

This was one of the scenarios that generated a spirited debate between the German philosopher and mathematician Gottfried Leibniz (1646–1716) and the British philosopher Samuel Clarke (1675–1729), a younger contemporary of Newton, and one of his defenders. Leibniz dismissed absolute space as an empirically empty fantasy, favoring his own relative conception. Although his system was metaphysical rather than scientific, and so not really a rival to Newton's, and although assuming absolute space helped Newton provide explanations of some observed events, Leibnitz had a point. If certain questions about position in absolute space, and about absolute velocities, can't be answered, or even supported by empirical data, then we might reasonably wonder whether it might be possible for us to replace absolute space in our theories, thereby avoiding unanswerable questions, without loss of explanatory power. If so, perhaps we should.

It is now known that Newton's laws can be translated into a theory that retains absolute time while giving up absolute space.[4] Absolute time is maintained by preserving Newton's linear, numerically measurable structure of moments of time, one following another at a constant rate. Although space remains 3-D Euclidean, there are no points of absolute space persisting through time. Rather, the universe through time is conceived of as a series of simultaneity slabs (one following another in time) each of which consists of a set of space-time moments or events (allowing for events at places in which nothing happens) occurring at a given moment. The space-time points on such a slab stand in measurable 3-D Euclidean relations to one another, even though those on one slab bear no spatial relation to those on other slabs. In other words, there are no common (absolute) spatial locations through time.

Nevertheless, one can trace relative spatial relations between distinct objects that persist through time. Changes in those relations can be visualized by imagining the slabs stacked vertically with lines connecting the occurrences of objects on lower slabs to the occurrences of those same objects on higher slabs (representing later times). The directions and distances between objects on a slab can be compared with those of the same objects on earlier and later slabs, indicating their relative movements over time. An object not subjected to external forces over a given period of time—i.e., a period in which the object, in Newton's original system, would either be at rest or in a state of uniform motion in a straight line—is represented in the new system as following a straight-line trajectory from lower to upper slabs (i.e., no distinction is made between rest and inertial motion over time).

In this framework, Newton's first law tells us that the trajectory (through time) of a body not acted on by external forces is a straight line. His second law says that when a force acts on a body, the trajectory of the body from lower to higher slabs is curved in the direction in which the force is applied, the amount of curvature being proportional to the amount of force applied and inversely proportional to the mass of the body. So, in a variant on the spinning bucket case, two globes connected by a cord and revolving around an axis running through the middle of the cord will remain at a constant distance from one another as they move from earlier to later simultaneity slabs, but their trajectories through space-time will be curved because of the constant force applied to them (as in the left side of the next figure). In this way, one accommodates the accelerated circular motions (rotations caused by the application of a constant force), without having to posit absolute space, thus avoiding the empirical conundrums to which it gives rise.

The next step toward the modern conception of space and time in physics was Albert Einstein's theory of special relativity, presented in his 1905 paper "On the Electrodynamics of Moving Bodies." The theory presented there describes a single inertial frame (where we don't have to consider the motions of any objects other than those within a limited physical system). It targets the notion of temporal

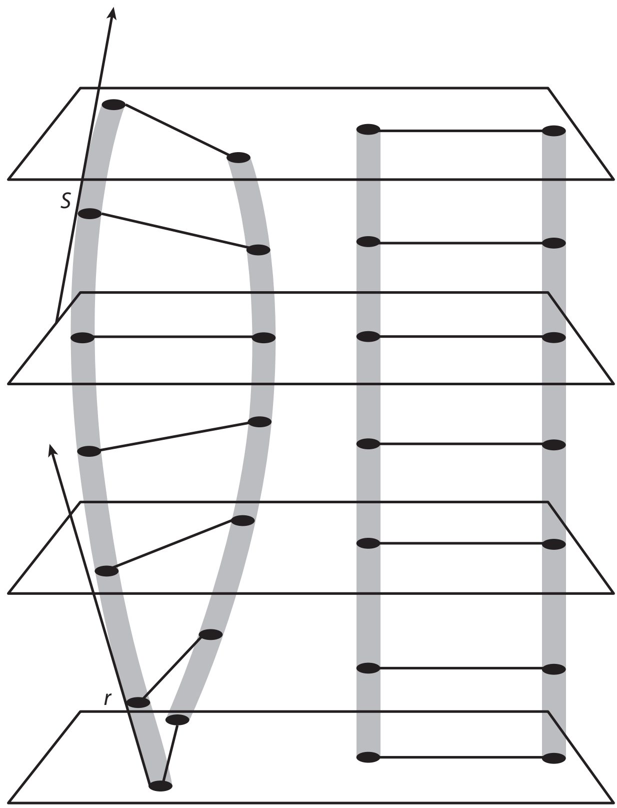


Diagram of rotating (*left*) vs. stationary globes (*right*).
From Maudlin (2012), p. 56.

simultaneity, giving up absolute time along with absolute space, thereby modifying our understanding of simultaneity.[5] One can get a sense of the change by considering how we normally establish the temporal simultaneity of two events occurring at a distance from one another. In daily life we judge two nearby events in our visual field to be simultaneous when we see them at the same time—when light emanating from one impacts our eyes at the same time as light emanating from the other. Since the distances are often short, this method works well for everyday purposes. But when we let the distances of the events from each other, and from the observer, vary, and become arbitrarily great, we need a method that takes into account the fact that the transmission of light from source to observer isn't instantaneous.

The idea can be illustrated by imagining synchronized (ideal) clocks present at the sites of two events A and B located at arbitrary distances from an observer. Each clock starts the moment its paired event occurs. The clocks are then transported to the observer through different paths at different speeds. If the speed of their transmission didn't affect their running, then an observer who knew the distance they traveled and their speeds could simply check their readings when they arrived. If one traveled twice as far but moved twice as fast, identical clock readings would register simultaneity of events.

According to relativity theory, however, the clocks' behavior is affected by their transmission through space.[6] If this sounds incoherent, it is probably because one is thinking of clocks as metaphysical know-not-what's that, by definition, track the passage of time, which, by definition, exists independently of any physical phenomenon. But that thought is unfounded. It's not true *a priori* that there must be such a thing as time conceived of in that way. Rather, the imagined clocks should be thought of as physical mechanisms, and so subject to physical laws. Because of this, it's not obvious that their behavior will be unaffected by their movement through space. Relativity theory maintains that their behavior is affected, thereby questioning the pre-theoretic idea of simultaneity.

Suppose we try to replace this idea with a physically defined notion of simultaneity applying to events at a distance. Let us say that for events at a distance to be physically simultaneous, and so not separated in time, is (essentially) for there to be no possible causal connection (e.g., by light from one reaching the other) between them. The argument of Einstein's 1905 paper shows that although physical simultaneity, so understood, is a symmetric relation (if x is simultaneous with y, then y is simultaneous with x), it's not transitive (x and z may fail to be simultaneous, even though x is simultaneous with y and y is simultaneous with z).

This result is illustrated by a sequence of events—A, B, C, and D—all occurring in that temporal order at point 1 in space, and another event Δ occurring at a spatially distant point 2. Event A is the emission of a ray of light at point 1 that travels to point 2. Its arrival there is event Δ, which, since it took time for the light to make the journey, occurs later than A. The ray is instantaneously reflected back to point 1; its arrival there is event D, which occurs later than Δ. Because the transmission of light is not instantaneous, events B and C, which occur at point 1 after A but before D, can't be connected by rays of light to the occurrence of Δ at point 2. (Since B follows A, light from B can reach point 2 only after Δ has occurred, and since C precedes D, light from Δ can't reach point 1 at the moment prior to D at which C occurs.) So there are no physical relations capable of causally connecting event Δ at point 2 with any events occurring at point 1 after A but before D.[7] This seems to suggest that events B and C at point 1, which occur after A but before D, are both physically simultaneous with Δ at point 2, even though B temporally precedes C.

But that seems impossible. Since we don't want one event to be simultaneous with two temporally nonoverlapping events, one of which is later than the other, we need to adjust our understanding of these relations. One way to do so is to let the relations simultaneous with, before, and after be undefined for pairs one of which is Δ and the other of which is any event in the temporal interval from A to D at point 1. If we do this, then these temporal relations will be physically grounded, but only partially defined. A different way out is to choose a unique event in the range of indeterminacy at point 1 and simply stipulate that it is to count as the event at point 1 that is simultaneous with Δ at point 2. The adoption of such a rule means that the simultaneity relation embedded in the theory will be partially a matter of convention or convenience, rather than a fully objective physical relation.[8] Einstein took the second option, offering a partially conventional synchronization rule for simultaneous events. This allowed him to assign a fixed numerical value to the speed of light, though different values could have been assigned had different conventions been stipulated.

Since, in special relativity, we give up absolute space and time, we must also modify our ordinary notions of motion, distance, and speed. When they are replaced with modified notions, the replacements don't have all the properties of the originals. Instead of independent time and 3-D Euclidean space, special relativity posits a 4-D space-time continuum, made up of points represented by coordinates <t, x, y, z>, each element of which represents an aspect, or dimension, of those points. Although t is called the temporal coordinate and the others are called spatial, the mathematical relations holding between the numerical quadruples that represent events reveal the physical interconnectedness of those dimensions, which is quite different from the independent variability of the dimensions in absolute space and time. This, in turn, yields surprising results involving motion, distance, and time.

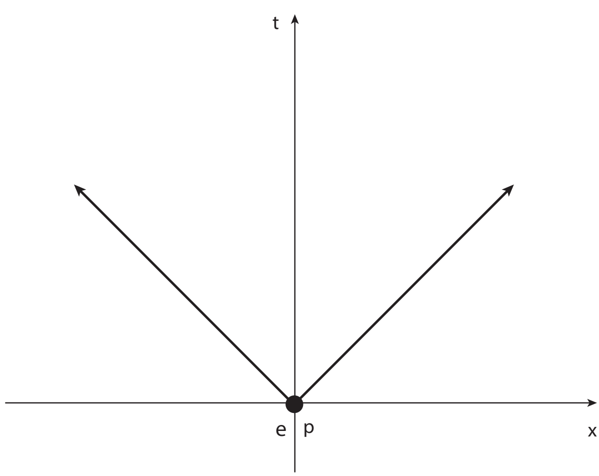
One law of special relativity involved in generating these results is the experimentally validated hypothesis that the movement of light in a vacuum is independent of the physical state of its source. In particular, light from two sources moving in opposite directions in a vacuum, each emitting light when passing one another, will arrive at any point in the universe at the same time. This would not be true of two physical objects initially moving in opposite directions, each, at the moment of passing the other, subjected to the same external force in the same direction (i.e., in the direction of movement of one of the two bodies).

Einstein's realization that this is so was a crucial step in the development of special relativity. In "Fundamental Ideas and Methods in the Theory of Relativity, Presented in Their Development," he says, "The phenomenon of magnetico-electric induction caused me to postulate the (special) principle of relativity."[9] According to Maxwell, a magnet at (absolute) rest is surrounded by a magnetic field, but when it moves, the magnetic field changes and an "induced" electrical field comes into being. Since the presence or absence of electric current should, in principle be detectable, the presence or absence of the current should tell us whether the magnet is moving in absolute space. However, Einstein knew that it couldn't play this role, since whether the induced field could be detected depended on whether or not the observer was moving in absolute space in sync with the magnet—something that could not, in principle, be determined.

Einstein's solution was to relativize space and time, thereby making the presence or absence of the electrical field an objective and observable effect of movement of the magnet relative to potential observers, each with their own space-time trajectories. But this posed the further problem of reconciling Maxwell's electrodynamics of light, which Einstein accepted, with relativity. According to Maxwell, light consisted of waves in an electromagnetic field. How, then, should one conceptualize the velocity of light? In the Newtonian framework of the late nineteenth century, the velocity of light from a source moving in the same direction as the source should be the velocity of the source plus the constant velocity of light, which for Maxwell was 186,000 miles per second. (For light from a source moving in the opposite direction one would subtract the velocity of the source from the constant figure for light.) Call this "the emission theory of light." When Einstein gave this up—positing that the state of motion of the light source doesn't affect when light from a point will reach other points—he was able to incorporate Maxwell's theory into special relativity.[10]

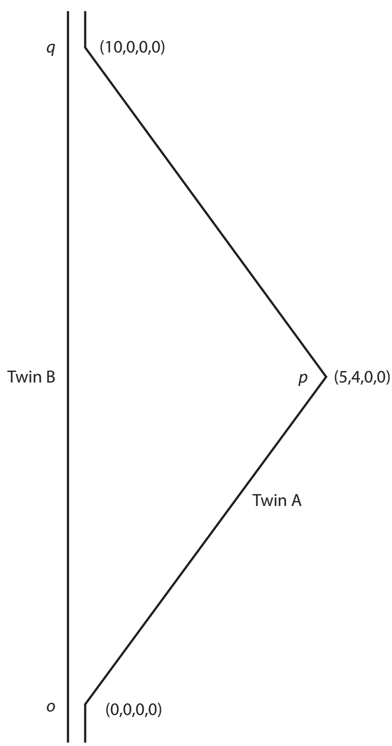
Another law of special relativity states that the path of a light ray emitted from a source in a vacuum is a straight line. One can represent this visually in two dimensions with a vertical temporal axis t, a horizontal spatial axis x, and a light-emitting event e at space-time point p. Ignoring the y and z spatial dimensions (and thinking in terms of a flat spatial plane), we may draw two lines from p at right angles to each other, each climbing vertically at a 45-degree angle (so the values of x and t always change by the same increment along the line). Everything between the lines is called e's future light-cone.

The idea that nothing goes faster than light is given by a further law: that the path of a physical entity passing through the future light-cone of an event e never goes



outside e's light-cone (which would require the x-value to change more rapidly than the t-value). To this we may add the relativistic law of inertia: The trajectory of any physical entity (light or a body with mass) not acted on by external forces is always a straight line.[11]

With all this in place, one can get an idea of how time is measured in special relativity theory. Movements are represented by lines, straight or otherwise, connecting space-time points through which something—physical objects or light—passes. The points are represented by four-dimensional numerical coordinates. The interval between two points is given by applying a mathematical formula to the pair of 4-D coordinates assigned to the two points. Given this, we can illustrate the hypothesized relation between time, space, and movement postulated by special relativity.



From Maudlin (2012), p. 78.

Suppose a pair of objects A and B are at rest relative to one another at a space-time point o, which, for simplicity, we will assign the temporal coordinate 0 and each spatial coordinate x, y, and z also 0. As explained by Tim Maudlin in *The Philosophy of Physics: Space and Time*, A and B are identical twins each in her own rocket ship.[12] B remains where she is throughout. A does not. By firing her rocket, she moves along the x spatial dimension only, arriving at point p, with temporal coordinate (t) 5, x coordinate 4, and y and z remaining at 0 (reflecting the fact that she is moving in just one of the three spatial dimensions). A then returns in the opposite x-direction, arriving at point q, where B is located, the temporal coordinate of which is 10, the x, y, and z coordinates 0. (B hasn't moved in any spatial dimension). Visualizing this on a two-dimensional diagram, the line connecting space-time point o where A and B start out with the space-time point q where both end up (B by staying put and A by moving) is a straight vertical line.[13] A's movement from o to p is a straight diagonal line from one to the other; A's movement from p to q is similar, resulting in an isosceles triangle.

The sides of the triangle with vertices o, p, q represent intervals through space-time. The special relativity formula for measuring them is a simple arithmetical computation on the <t, x, y, z> coordinates of the endpoints of the three lines o to q, o to p, and p to q. For each line, the number we get, which measures its spatiotemporal trajectory, is the square root of n, where n is the square of the difference in the temporal coordinates of the endpoints, minus the square of the difference in their x coordinates, minus the square of the difference in their y coordinates, minus the square of the difference in their z coordinates.[14] Since the y and z coordinates are irrelevant in our example, the interval from point o to point q is assigned the square root of 10^2 minus 0, which is 10. The interval of A's journey from point o to point p is the square root—namely 3—of 5^2 minus 4^2 (where 5 is the difference in the t coordinates and 4 is the difference in the x coordinates). Not surprisingly, the interval of A's journey from point p to point q is the same. Thus the measure of A's entire journey from o to q is 6, while the measure of B's journey is 10.

So special relativity tells us that A's journey through space-time is shorter than B's—in fact it is $3/5$ of B's. But, what, you may ask, is measured? Time is measured. The time A lived through by first moving away from B to p and the returning to B at q is less than the time B lived through by waiting for A to rejoin her.[15] Thus, although A and B were (we may imagine) exactly the same age when they were together at o, and although both are older at q than they were at o, A is now younger than B. Whatever amount of time B experienced in going from point <0,0,0,0> to point <10,0,0,0>, say 100 days, A experienced 6⁄10 of that, or 60 days. If both had accurate clocks with them (whatever physical mechanisms might count as such), A's would register 30 days when reaching p and 60 days when reaching q, while B's would register 100 days while reaching q. In effect, A's clock would tick more slowly than B's. But it would not fail to keep correct time. According to special relativity, both clocks are correct. What the example shows is the essential interdependence, rather than independence, of space and time, and its consequences for our understanding of movement through space and time. This, special relativity tells us, is what space-time is really like, quite apart from how we are intuitively inclined to think of it.[16]

So far, we have simply assumed that clocks in our examples keep correct time. All that can be said at this point about what physical processes count as clocks is (i) that if they are on the same trajectory (moving neither nearer nor further from one another), they will, when synchronized, display the same time and "tick together," (ii) that if they are moving apart (like the clocks of A and B on A's journey away from B), each will seem to the other to be running slow, and (iii) that if they are moving toward one another (like the clocks of A and B on A's journey back to B), each will seem to the other to be running fast (even though overall, A will have expended less time in her journey than B will have expended standing still).[17] Ultimately, of course, these clocks have to be physical entities, which, one can demonstrate by experimental test, will perform as the theory predicts.

Although the experimental tests are difficult and complicated, there have been such demonstrations. The idea is often illustrated by imagining a pair of mirrors, between which a ray of light bounces—each round trip of the light between the mirrors counting as a "tick" of the clock.[18] In order for the mechanism to count as a clock, the intervals measured by each tick must be the same. As Maudlin explains, this condition will be violated unless, as Einstein proposed, the mirrors are connected by a rigid rod as they move through space-time. Without it, special relativity predicts that changes in velocity resulting from a force acting on the two mirrors would lengthen the intervals after the force is applied, destroying the system's ability to function as a clock accurately measuring time for the journey as a whole. According to relativity theory, the rigid rod connecting the mirrors prevents this by physically contracting as the force is applied, pulling the mirrors closer together in just the amount needed to keep the intervals traveled by the light back and forth between the mirrors the same.[19] In other words, the spatial distance between the two mirrors, as measured from the perspective of the original reference frame (before the force was applied), contracts in a way that preserves the length of the intervals traveled by the light. This is the sense in which the speed of light is constant in special relativity, even though there is no absolute space or time to objectively measure speed independent of any frame of reference.

Subjecting special relativity to empirical test is complicated by the fact that the temporal intervals of round trips between mirrors in a laboratory are too short to be reliably measured by ordinary clocks. But the fact that the speed of light is constant in the way predicted by relativity theory can be tested empirically. One such test involves a light source emitted from a spatial location p in line behind a pair of rapidly spinning discs (one behind and at some distance from the other) connected by a rapidly spinning rod. Each disc has a small slit in it through which light might pass. The light source shines on the rear disc, resulting in some light passing through its slit as it spins. If the light passing through reaches the space occupied by the slit in the rotating second disc, the light will pass through it and illuminate the screen behind the apparatus; otherwise it will be blocked by the second disc. By adjusting the speed of the discs, as well as the placement and the angle of the slits, it is possible to put the system into a state in which the light from p always gets through. Relativity theory predicts that this will remain true whether the source emitting light at p is at rest, or is moving toward or away from the apparatus. This has been verified.

A second experiment puts this apparatus on a floating platform that can be turned in any direction, e.g., facing north, south, east, or west. Because of the rotation of the earth and its revolution around the sun, these changes in orientation of the apparatus relative to the earth's rotation, as well as changes in the velocity of the earth's movement around the sun at different times, might—as far as one could know before putting it to the test—result in small changes in the speed of light passing through the slits of the apparatus. If so, the device would have to be recalibrated when its orientation in the laboratory is changed, or when it is used at different times of the year. Special relativity predicts this will never happen, and it doesn't.[20] One can also put the apparatus in motion in a straight line and determine whether the slits have to be adjusted for the light to pass through, depending on whether the light source moves with the apparatus or is stationary relative to it. As predicted by special relativity, they don't.

Einstein's theory of *general relativity*, which emerged ten years after he developed special relativity, introduced a new way of understanding gravity, which was accompanied by a new relativistic conception of the structure of space-time. In the new structure, the shortest distance between two points is a curved line, as it is on the surface of a sphere. In addition, parallel lines that intersect the same line at an angle of 90 degrees may, if extended far enough, intersect one another, just as the lines of longitude on the surface of the earth intersect one another at the poles, despite intersecting the equator at right angles. Nevertheless, Einstein didn't think of space-time as having the uniform geometry of the surface of a sphere. Rather, its curvature is variable. Unlike parallel lines on a sphere, parallel lines on a portion of space-time with a concave curvature can diverge from one another as they are extended. Space-time as a whole was not thought of as having a single type of curvature everywhere.

If the geometry of space-time is, as Einstein says, variable, what determines, or at any rate influences, that variability? The answer is, the distribution of matter in the universe. This is where gravity comes in. As we know, Newton thought of it as a force acting on bodies, proportional to their mass, which changes their trajectories through absolute space and time, pulling them closer together. By contrast, in developing general relativity, Einstein came to think of the mass of material bodies as bending the curvature of space-time itself, proportional to the mass of the bodies. Since light always follows the geometry of space-time, this means that the observed trajectory of light from a distant body will increase its curvature around a massive body in its path, seeming to an observer on the other side of the body to "bend" around it. This fact was experimentally confirmed in 1919 by Arthur Eddington, whose photographs of a solar eclipse demonstrated the bending effect.

Though this was rightly hailed as vindicating general relativity, talk of "bending" shouldn't be misunderstood. In following the locally curved path, light was doing what it always does: moving along the shortest physically possible path in space from one point to another.

More recent observations have provided further confirmation of general relativity. One involves a quasar 8 billion light-years from the earth, with a galaxy 400 million light-years away from us and intervening between us and the quasar. This galaxy, which is a massive collection of matter, bends the space-time through which the light passes, resulting in the appearance to us of a cluster of four images of the same star. In addition, the rotation of the earth has been shown to produce a disturbance in space-time around it, caused, according to general relativity, by rotation of a massive body. This was observed as the change in the axes of gyroscopes in a satellite—Gravity Probe B (GP-B)—in 2004. The principal investigator, Francis Everitt of Stanford University, explained the results this way.

> Imagine the earth as if it were immersed in honey. As the planet rotates, the honey around it would swirl, and it's the same with space and time. GP-B confirmed two of the most profound predictions of Einstein's universe, having far-reaching implications across astrophysics research.[21]

One of the most fascinating discussions of the way in which gravity is understood in general relativity involves Richard Feynman's discussion of Galileo's famous experiment showing that the velocity with which bodies of varying masses (e.g., a bowling ball vs. a marble) dropped from a tower are not affected by their mass; except for air resistance, they fall at the same rate and so land together.[22] The reason for this in Newton's framework is that although the gravitational effect on a body by other bodies is proportional to its mass, the resistance of the body to the gravitational effects of other bodies is proportional, in exactly the same degree, to its mass. Hence, these two features of mass cancel each other out, and, Newton explains, the marble and bowling ball hit the ground at the same time.

By contrast, in general relativity the bowling ball and the marble are free of all forces after being dropped, and so follow straight (i.e., shortest) spatial trajectories, much like twin B in the earlier example, who, remaining at rest, was subjected to no forces during A's journey. *In Galileo's case, the tower and any clocks at the top or bottom of the tower continue to be moved by forces deriving from the earth's movement—rather like twin A was moved away from twin B when she fired her rockets.* With this in mind, suppose there are two synchronized clocks at the base of the tower. One, Clock A, remains there; the other, Clock B, is thrown upward precisely when Galileo drops the marble and bowling ball—thrown with just enough force so as to hit the ground the moment the marble and the bowling ball do. Just as twin A's accelerated motion relative to twin B resulted in more time elapsing for B than A between A's departure and return, so, Feynman observes, the account of gravity in general relativity predicts that the accelerated motion of Clock A (on the ground) throughout the flight of Clock B—which, in the second half of its trajectory, is free of forces and undergoes no acceleration—results in more time elapsing for (and being recorded by) Clock B than Clock A. (The same would be true if clocks were dropped along with the bowling ball and marble.) This, it has been reported, has been confirmed.[23]

Up to now, in speaking of Newton, Einstein, and others, I have mostly been concerned with macroscopic objects and events, which came to be understood much better in the twentieth century than they ever had been before. The twentieth century also saw stunning developments in our understanding of the universe at the microscopic level, including atomic and subatomic states and particles. The work of Max Planck and Albert Einstein on radiation and light early in the century was followed by Niels Bohr's theory of the atom, and the mathematical formalisms for describing the subatomic world developed by Max Born, Werner Heisenberg, Erwin Schrödinger, and Paul Dirac. The result was the spectacular success of quantum mechanics in precisely measuring and predicting subatomic events and processes. Paradoxically, this predictive success wasn't matched by a comparable advance in our ability to connect the micro-level of reality with the macro-level, or to even understand what micro-level facts generate the well-attested micro-level predictions we are able to make. Simply put, quantum physics is telling us something about the universe, but we don't yet know what it is.

The point can be illustrated with a simple abstract example. Suppose we arrange for particles of type P to traverse a region of space by one or the other of two possible routes, A and B, from which the particles emerge, continue on, and end up in places C or D. Having the ability to test whether a particle takes route A or B, we wish to know which of the two possible destinations it will arrive at when it takes those routes. So we set up an unobtrusive measuring device that displays 'A' or 'B' depending on which route the particle takes. When we run experiments, we find that 50% of the particles that take route A end up at place C and 50% end up at D. The same is true for route B. So, we are confident that we can turn off the monitor, knowing that running more particles through the region of space will always result in 50% ending at C and 50% ending at D. Surprisingly, however, we are wrong. With the monitor off, 100% of the particles arrive at place C and none arrive at D![24]

How can that be? Surely, one is inclined to think, either there must more than two routes or our measurements monitoring the routes are faulty. It turns out, however, that there aren't more routes and we aren't mismeasuring the particles going through them; every measuring device produces the same results. Thus, we are forced to conclude, measuring the particles somehow changes the reality we are trying to measure. But how? There is no consensus about this among quantum physicists or philosophers of physics.

There is, however, an accepted vocabulary for describing the situation and making probabilistic predictions. In quantum physics it is commonly said that certain properties of a particle don't exist until you measure them—or, at any rate, that it doesn't make sense to say that they have the properties, or fail to have them, until you measure them (at which point they definitely do or definitely don't have the properties). It is not clear what, if anything, is said to exist (prior to measurement), but it certainly *sounds* as if there is a *wave function* associated with the particle (or other entity)—a kind of smear of energy that can be represented by a mathematical function that contains information encoded in positive or negative numerical values.[25] Think of these numbers as measuring the amplitude—height (positive numbers) or trough (negative numbers)—of the wave. From these we calculate the *probability* that an entity has one or another property. The probability is the square of the measurement of the amplitude of the wave, so, in standard cases, the probability calculated from an assignment of a positive number n is the same as that resulting from its negative counterpart –n. As we will see, however, in special cases assignments of n and –n to the same possible outcome cancel out before the final probability is calculated. This is crucial to predicting differences between the behaviors of measured vs. unmeasured particles.

Proponents of the once standard Copenhagen interpretation of quantum physics sometimes seemed to want to say that an *unmeasured* particle (or other entity) has a certain probability of having a given property P, while refusing to say that it either does have P or doesn't have P prior to being measured, and suggesting that both the claim that it does and the claim that it doesn't are meaningless. This challenge to classical logic is troubling, in part because it isn't clear what it would mean to say that the statement "the probability *that x has P* is so-and-so" is true (and hence meaningful), if the claim *that x has P*—to which you have assigned a probability—is either meaningless, or a claim that couldn't possibly be true. It is one thing to assign a probability to a claim one doesn't, and perhaps can't, *know* to be true; it is another to assign a probability to a claim that one takes to be meaningless (or to a claim that one knows *could not possibly be true*).

Things are improved if we modestly revise the above, perhaps incautious, characterization, by saying simply that the claim that an *unmeasured* particle (or other entity) has a certain probability of *being measured as having property P* is true—while continuing to take the claim that it has a certain probability of *being P,* or of *not being P,* to be meaningless. Although this terminological revision doesn't remove the violation of classical logic, at least the claim it makes is not so obviously incoherent. Nor does the revision resolve the mystery of how mere measurement could *bring it about* that the wave function associated with a particle "collapses," and the particle *comes to have* the seemingly independent property of *being P,* or of *not being P.*[26]

With this in mind, let us return to our example of particles traversing different routes, A and B, to final positions C or D. When we measure the routes taken, we find that half the particles observed to travel through route A, and half those observed to travel through route B, end up at position C, while the rest end up at D. But when no measurement of the trajectories takes place, they all end up at C. Quantum physics has a way of accommodating this. Allowing wave functions associated with particles to take negative numbers among their values makes it possible to predict that certain possibilities will cancel each other out in a way that yields determinate results, even though in other cases no such canceling occurs and only probabilities can be predicted.

When, in our example, there is no measurement of particles passing through routes A or B, the wave function assigned to the particle generates a determinate outcome—arrival at position C. This result is reached in roughly the following way. First, the numerical value 0.7071 (which when squared would give us the probability 0.5) is assigned to arriving at C via route A; the same number is assigned to arriving at D via A. Second, 0.7071 is assigned to arriving at C via route B (no surprise), but the value assigned to arriving at D via route B is –0.7071. Because we have positive and negative values assigned to *the same outcome,* namely arriving at D, the rules of quantum mechanics tell us to sum these values before determining the final probabilities. Since their sum is 0, and since 0 squared is 0, we generate the prediction that the probability of arriving at D is 0. This, together with the reinforcing values for arriving at C, results in the prediction that the probability of arriving at C is 100%.[27]

What happens when we *measure* the particles moving through routes A and B? Since we know that measurement affects outcome, the relevant wave function is *not* associated simply with a particle; it is associated with *the pair* consisting of the particle and the measuring device, which, we may imagine, will be in one of two states, displaying 'A' or displaying 'B', immediately after measurement. As before, the wave function gives us numerical values for four states: (i) the value of the state consisting of the particle arriving at C after being correctly measured to follow path A is 0.7071, *0.7071 (particle at C, device measures 'A')* for short, (ii) the value of the state consisting of the particle arriving at D after being correctly measured to follow path A is also 0.7071, *0.7071 (particle at D, device measures 'A')* for short, (iii) the value of the state consisting of the particle arriving at C after being correctly measured to follow path B is 0.7071, *0.7071 (particle at C, device measures 'B')* for short, (iv) the value of the state consisting of the particle arriving at D after being correctly measured to follow path B is –0.7071, *–0.7071 (particle at D, device measures 'B')* for short.

Note the two italicized values involving arrival at D, one positive and one negative. Because the states assigned these amplitudes include *different states of the measuring device*, the states to which the positive and negative numbers are assigned are themselves *different*. Thus, the intrusion of measurement makes it impossible to sum or combine these values. This means that nothing sums to 0 and there is no cancellation, as there was when there was no measurement. As a result, a particle correctly measured as running through A has a probability of 50% of ending at C and a 50% probability of ending at D, and similarly for a particle correctly measured as running through B. This fits our observations: half the particles measured as running through A do end up at C and half end up at D; and half the particles measured as running through B do end up at C and half end up at D.

Getting the mathematics to work out this way was an achievement, which, once systematized and mastered, allowed physicists to make incredibly precise and surprising predictions. *But what reality is described by the assignment of probabilities to quantum states?* How and why does measurement prevent the cancellation of possible outcomes in our example? What physical reality is represented by cancellation vs. non-cancellation? Suppose we think of it this way. States of the particle (in the unmeasured case) and of the particle-measuring device pair (when we measure the routes taken) are physical situations that cannot causally interact with one another. The particle, when unmeasured and left to its own devices, always arrives at position C; physical laws determine this result. But when measurement is introduced we are left with two equally probable possibilities—arriving at C and arriving at D.

If we don't say that measurement changes the laws of physics—as it would seem we shouldn't—then we must say either that measurement introduces some real but previously unimagined element, or that measurement is somehow faulty. One possibility, espoused by the physicist David Bohm, is that some further hidden element, or variable, not caused by the measuring device, but somehow interacting with it, must be involved.[28] A different idea developed initially by Hugh Everett III in his 1957 doctoral dissertation in physics at Princeton has, after decades of neglect, now begun to attract more attention.[29]

Suppose, Everett imagined, that measurement (somehow) causes a single particle-plus-measuring device to split into a pair of such systems—particle p1 + measuring device 1 and particle p2 + measuring device 2. Suppose further that one of these particles reaches C, and is measured by its companion device as doing so, while the other reaches D, while being similarly measured. *We* don't observe the latter because, despite being just like p1, p2 is causally isolated from p1, and so incapable of interacting with p1 in any way at all, *including being observed by us to arrive at D when p1 arrives at C*. From the moment of its creation, p2 is in a part of the universe inaccessible to us and our measuring device. The laws of physics determine that whenever a particle of type P is *measured* passing through routes A or B, a duplicate is created that will arrive at D when the original arrives at C.

That, of course, is not all. Being incapable of interacting with p1, p2 is also incapable of interacting with anything causally related to p1, including us, our measuring device, anything causally interacting with us or our device, anything interacting with anything that interacts with us or our device, and so on without end. In short, certain quantum events, including (but not limited to) those that occur in actual, conscious measurement, open up new dimensions of reality, new "worlds" in Everett's sense, obeying the same deterministic laws as those in our dimension (world). These dimensions can be thought of as populated by "copies" of all entities in our dimension—including us, our measuring device, anything interacting with us or our measuring device, and so on without end. Despite traveling through different futures, these emerging entities share a common history with us and our dimension-mates.

In fact, we may not have to think of any of the elements in different dimensions ("worlds") as copies. Perhaps, after measurement, there is just one particle, just one measuring device, and just one observer, continuing on different futures in the different dimensions. Just as there is no contradiction between my being a young philosopher at t1 and my not being a young philosopher at t2, so there is no contradiction between (i) my observing p1 to arrive at C, and not D, *in dimension 1,* and (ii) my observing p1 to arrive at D, and not C, *in dimension 2.* According to this way of conceptualizing things, when *in dimension n,* I measure a particle going through either route A or route B, I come, *in dimension n,* to observe that particle as ending up at C or D, but not both, while coming, in *dimension n+1,* to observe it at the other of the two. Obviously, this can be iterated when further particles are observed passing through the routes. By contrast, if, in either dimension, I send a particle through without checking the route, I always see it ending up at C. In this way, my experience through the different dimensions will match the predictions derived from quantum mechanics.

This, in oversimplified form, is what is called the "many-worlds" conception of quantum mechanics. Though philosophically and mathematically brilliant, Everett's astounding idea was, understandably, too radical and too underdeveloped conceptually for the establishment physicists and philosophers of his day. However, his idea has been more fully fleshed out over time, and has now become one of the leading interpretations of quantum mechanics. Today, it is defended and elaborated by such luminaries as David Deutsch, professor of physics at Oxford University, David Wallace, professor of philosophy at University of Southern California, and Sean Carroll, professor of physics at California Institute of Technology (Caltech), as well as a number of others.[30] Its growing success appears to be attributable to the facts that (i) the reality it postulates bears a close relationship to the mathematical formalism of quantum theory, allowing it to be read as a straightforward description of the seen, and unseen, world, and (ii) it explains the probabilities predicted by the theory in a way that is consistent with deterministic physical laws. The same cannot be said for other leading interpretations.

Nevertheless, the many-worlds interpretation remains highly controversial, in part because of the profoundly perplexing philosophical issues it raises. For this reason it seems likely that the future debate over what our most advanced physical theory is telling us will be fought out on the common ground occupied by physics and philosophy. That much, at least, shouldn't be surprising. Twenty-four centuries after Aristotle's observation that human beings by nature desire to know, neither the desire, nor the need for philosophical clarification of perplexing possibilities encountered in trying to satisfy it, have lessened in the slightest.