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Time in fundamental physics

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ABSTRACT

The first three sections of this paper contain a broad brush summary of the profound changes in the notion of time in fundamental physics that were brought about by three revolutions: the foundations of mechanics distilled by Newton in his *Principia*, the discovery of special relativity by Einstein and its reformulation by Minkowski, and, finally, the fusion of geometry and gravity in Einstein's general relativity. The fourth section discusses two aspects of yet another deep revision that waits in the wings as we attempt to unify general relativity with quantum physics.

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1. Newton's abstraction and its success

We perceive the passage of time through change. However the existence of change by itself does not establish the reality of an *objective* time. Indeed, our direct observations refer to a *relational* notion of time. For example, routine measurements only tell us that while the earth goes around the sun once, the moon goes around the earth approximately 13 times. Or, while the second hand completes one round on one's wristwatch, one's pulse beats 70 times. What we directly experience is change and observations only let us compare durations involved in one change with those involved in another. This led to what is often referred to as the Leibnizian space–time view in which the only meaningful questions about motion refer to relative motion.

This notion of relational time has a curious similarity with the barter system people used before the advent of the abstract concept of money. A sheep was worth n chickens, a chicken was worth m bottles of oil, and so on. People only *compared* values of objects. Money—particularly in the form of banknotes—is an abstract concept, a mental creation, that simplifies trade. Money is not essential for survival. One can imagine abolishing money and using just the barter system that only assigns relative values to pairs of necessary objects. But the notion of money is extremely powerful: it *streamlines* all commercial transactions by giving each item an absolute value in place of the pairwise relational values used in the barter system. It is difficult to imagine a flourishing trade without money, let alone the more abstract monetary instruments that are now used.

Through his *Principia*, Newton streamlined time in the same fashion. He postulated that *absolute time* in itself has a direct physical meaning, without reference to any physical systems or phenomena. To distinguish this notion from other subjective or psychological measures of the passage of time, he represented the absolute physical time by a 1-dimensional mathematical continuum.[1] All durations were to be measured against this absolute time. Newton taught us that we need not be satisfied with *relational time*, e.g., just with thinking of how many rotations of the moon around the earth correspond to one rotation of the earth around the sun. Rather, the moon's orbit around earth marks an interval on the *physical* one dimensional continuum of time by

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[1] In the contemporary terminology used in the general relativity literature, what Newton called absolute space provides a canonical foliation of space–time and each slice is labeled by a value of the time parameter (taking values in the one-dimensional affine space $\mathbb{R}$). The preferred family of observers are the Galilean ones, in uniform motion with respect to one another. They all agree on this parametrization. What I call Newtonian space–time in this paper is generally referred to as *neo-Newtonian* or *Galilean* space–time in the history and philosophy of science circles following Erman (1989). I thank Tom Pashby for pointing this out.

itself, and so does the earth's orbit around the sun. Any inertial observer can measure these intervals and Newtonian mechanics asserts that they will all agree in spite of the uniform relative motion. Thus, the flow of time is absolute in spite of Galilean relativity. *If we wish*, we can compare the lengths of these intervals and conclude that there are approximately 13 moon-orbit intervals in one earth-orbit interval. And we can also compare these intervals with those marked on the absolute time continuum by the rotation of the second hand on one's watch or one's pulse. But the comparisons and the resulting relational notion of time are all secondary. Absolute time is the primary, physical notion.

This notion lies at the foundation of Newton's laws of mechanics. The resulting celestial mechanics were astonishingly successful. Already in the 1750s, papers appeared in the Philosophical Transactions of the Royal Society, calculating sophisticated consequences of Newton's laws, such as of the effect of the gravitational pull of Jupiter and Saturn on earth's motion (see, e.g., Walmesley, 1756)! Had one continued to use the relational time of direct experience—as Leibniz, for example, advocated—such calculations would have become very cumbersome. Celestial mechanics could be developed and its predictions could be compared against observations so quickly largely because it was based on Newton's absolute time.

The success of celestial mechanics brought home the message that the heavens are not so mysterious after all; they were brought within the grasp of the human mind. Thus, the *Principia* shattered Aristotelian orthodoxy by abolishing the distinction between heaven and earth. For the first time, there were truly universal principles. An apple falling on earth and the planets orbiting around the sun were now subject to the same laws, formulated using the same absolute time continuum. No wonder then that *Principia* literally sculpted human consciousness, providing the mental images that people commonly use. Most people now think of time as a part of physical reality, flowing serenely, all by itself, untouched by the external world.

In spite of this success, Newton was well aware of the fact that there was no objective basis for his postulates on absolute time and absolute space. He had to invoke theological arguments in support of their absolute character. Not surprisingly, Leibniz criticized these arguments as untenable.

2. Special relativity: abolishing absolute time

The *Principia* quickly replaced Aristotle's four books on physics and became the new orthodoxy. It reigned supreme for over 150 years. However, a challenge to the Newtonian world view then emerged from totally unexpected quarters: advances in the understanding of electromagnetic phenomena. In the middle of the 19th century, the Scottish physicist James Clerk Maxwell achieved an astonishing synthesis of all the accumulated knowledge concerning these phenomena in just four vectorial equations. These equations further provided a specific value of the velocity c of light. But this velocity did not refer to a reference frame; *it appeared as an absolute constant of Nature*. Now, the notion of an absolute velocity blatantly contradicts Galilean relativity, a cornerstone on which Newtonian mechanics rests. This tension between Maxwell's electrodynamics and Newtonian mechanics dismayed natural philosophers. But by then learned men had developed deep trust in the Newtonian world and therefore concluded that Maxwell's equations can only hold in a specific reference frame, called the *ether.* The value of the speed of light c that emerged from Maxwell's equations, they concluded, is relative to this ether. But by doing so, they in fact reverted back to the Aristotelian view that Nature specifies an absolute rest frame. A state of confusion remained for some 50 years.

There were several leading figures such as Henri Poincaré and Hendrik Lorentz who attempted to resolve this tension through mathematical modifications of the Galilean transformations. However, it was Albert Einstein who grasped the deep physical implications of this quandary: *It was asking us to abolish Newton's absolute time.* In 1905 Einstein accepted the implications of Maxwell's equations at their face value and used simple but ingenious thought experiments to argue that, since the speed c of light is a universal constant, the same for all inertial observers, Newton's notion of absolute simultaneity is physically untenable. Spatially separated events which appear as simultaneous to one observer cannot be so for another observer, moving uniformly with respect to the first. The Newtonian model of space–time can only be an approximation that holds when speeds involved are all much smaller than c. A new, better model of space–time structure emerged and with it a new kinematics, called *special relativity.*

In special relativity the elementary notion is that of an event—e.g., the explosion of a firecracker—which is completely localized in space and in time. These events constitute the space–time continuum. Strictly, this is also the case in Newtonian mechanics. What changes in special relativity is that *time no longer has a privileged standing.* Already in Newtonian mechanics, the spatial distance between two *events* separated by time is not absolute; it depends on the state of motion of the Galilean observer. In special relativity, time joins space: time intervals between two distant events also depend on the state of motion of the observer. Minkowski realized and emphasized the profound implication of this change: in special relativity, only the *4-dimensional* space–time continuum and its geometry are observer-independent.[2]

This new paradigm immediately led to some dramatic predictions. Energy and mass lost their identity and could be transformed into one another, subject to the famous equation $E=mc^2$. Since the velocity of light c is so large in conventional units, the energy contained in a gram of matter can therefore illuminate a town for a year. It predicted that a twin who leaves her brother behind on earth and goes on a trip in a spaceship traveling at a speed near the speed of light for a year would return to find that her brother had aged several decades. The origin of these astonishing consequences lies in the replacement of Newton's absolute time by the special relativistic *observer dependent* time. But they are so counter-intuitive that, as late as the 1930s, there were debates in prominent western universities whether special relativity could be philosophically viable. But we know that these misgivings were all completely misplaced. Nuclear reactors function on earth and stars shine in the heavens, converting mass into energy, obeying $E=mc^2$. In high energy laboratories, particles routinely reach velocities close to that of light and are known to live orders of magnitude longer than their twins at rest on earth.

More generally, we now routinely encounter billions of applications of special relativity both in frontier science and in gadgets used in everyday life. They provide convincing evidence that the absolute time of Newton's does *not* correspond to physical reality. It is an approximate concept that is very useful in situations in which all speeds involved are low compared to that of light (as is the case in celestial mechanics). Special relativity led us to a more sophisticated notion in which the absolute distinction between

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[2] In special relativity, space–time is still represented by the 4-dimensional affine space $\mathbb{R}^4$. However, there is no longer a preferred foliation of this continuum into space and time. Each inertial observer introduces her own foliation and can speak of space and time intervals between any two events. But as we change the observer, the values of these intervals change, leaving only the space–time interval invariant. In the Newtonian space–time of footnote 1, there is a preferred spatial slice through each event, labeled by the value of absolute time. In special relativity, through each event one has instead a light cone, trajectories of light rays emanating (and converging) at that event. In the limit $c\to\infty$, these cones become the spatial slices of absolute Newtonian time.