Elegant Connections in Physics
‘Time’ [Absolutely] Does Not Exist

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The eighteenth-century German poet Johann Gottfried Herder gave us this wonderful little introspective poem, *Das Leben*, or *Life:*[1]

> ***A dream, a dream is our life***
> ***here on earth.***
> ***Like shadows on the billows***
> ***we float and vanish.***
> ***And measure our slothful steps***
> ***by space and time.***
> ***And are (and know it not) in the***
> ***midst of eternity.***

***Das Leben* reminds us that Benjamin Franklin observed, “*But dost thou love life, then do not squander time, for that’s the stuff life is made of as Poor Richard says.*”[2] But what *is* “Time?” Questions on the nature of time are as old as they are fundamental. Almost two millennia ago, Augustine (354-430) asked such questions.[3] He wrote:**

What, then, is time? If no one asks me, I know what it is. If I wish to explain it to him who asks me, I do not know. Yet I say with confidence that I know that if nothing passed away, there would be no past time; and if nothing were still coming, there would be no future time; and if there were nothing at all, there would be no present time.

But then, how is it that there are the two times, past and future, when the past is now no longer and the future is now not yet? But if the present were always present, and did not pass into past time, it obviously would not be time but eternity. If, then, time presentBif it be timeBcomes into existence only because it passes into time past, how can we say that even this is, when the cause of its being is that it will cease to be? Thus, can we not truly say that time is only as it tends toward nonbeing?

Fast forward some 1200 years, when thinking on the nature of time had precipitated into two philosophical schools. These were the “absolute” and “relational” schools. Each position was well articulated by the founders of the Enlightenment. The champions of absolute time were led by René Descartes and Isaac Newton. Carrying the flag for time as a system of relations was Gottfried Leibniz.

Before going any farther, we must acknowledge that we cannot separate the question “What is Time?” from the equally deep questions, “What is Space?” and “What is Motion?” Although we can grasp the meaning of the width of my classroom or the (perhaps excessive) time of my lecture, are not these merely measures of space and time *intervals*, not Space itself and Time itself? Motion is the changing of a body’s position *in* space with respect *to* time; but how do we measure time? We measure time by counting cycles of some periodic motion, such as the swing of a pendulum, the spin of the Earth, or the frequency of a spectral line. And how do we measure space? By counting the number in times a standard of length must be translated to cross that space, which means our length standard must undergo motion.... It seems that thinking about motion and space and time gets us going in circles. So it’s not surprising, when we come to the early articulations of the Nature of Time, to find the proponents of absolute time also advocating for absolute space, and the proponents of relative time also arguing for space as a system of relations.

Descartes held that a material thing has a volume, and space occupies volume; therefore, space must be a *thing*. He wrote:[4]

The nature of matter...[is] simply in its being a thing that has extension in length, breadth, and depth... It is easy to see that it is the same extension that essentially constitutes a body and a space...

The impeccable logic of his next argument is delightful:

It may be asked what would happen if God removed all the body contained in a vessel, and allowed no other body to come and take the place of what was removed. The answer must be in that case that the sides of the vessel would ipso facto be in contact; for when there is nothing between two bodies, they must necessarily touch each other.

In the *Principia*, Newton made his assumptions about space and time explicit. He wrote:[5]

Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external...

Absolute space, in its own nature, without relation to anything external, remains always similar and immovable...

All motions may be accelerated or retarded, but the flowing of absolute time is not liable to any change. The duration or perseverance of the existence of things remains the same, whether the motions are swift of slow, or none at all; and therefore this duration ought to be distinguished from what are only sensible measures thereof...

For Newton, the time interval and the space interval between two events are separately invariant. This led to the Galilean transformations of Newtonian relativity, with its logical consequence that the speed of light, like any other speed, should depend on the relative motion between observer and source. Time invariance was also assumed in the equations of motion that apply in an accelerating reference frame, where we encounter the so-called Coriolis and centrifugal forces. In Newtonian relativity, when transforming from one inertial frame to another, or from an inertial to a noninertial reference frame, the *same* time differential dt is used.

Newton’s assumptions about absolute space and time were heartily criticized by Christian Huygens and George Berkeley, and especially by Gottfried Leibniz. The latter attacked with gusto Newton’s philosophy of space and time in a lively series of letters

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that he exchanged with Newton's follower Samuel Clarke. In one response to Clarke, Leibniz wrote:[6]

So for my own opinion, I have said more than once, that I hold space to be something merely relative, as time is; that I hold it to be an order of coexistences as time is an order of successions.

In order to prove that space, without bodies, is an absolute reality, the author objected that a finite material universe might move forward in space...I answered,...such a motion would produce no change that could be observed...The author replies now, that the reality of motion does not depend on its being observed...I answer, motion does not indeed depend upon being observed, but it does depend upon being possible to be observed...

Leibniz applies the same criteria about observability to the notion of absolute time:

Supposing any one should ask, why God did not create ever thing a year sooner...There is no mark or difference, whereby it would be possible to know, that the world was created sooner...

Leibniz has here identified two points that are crucial to science in general and to physics in particular. First, he has identified the feature that makes science distinct from other ways of thinking about the world; and second, he has pointed to the importance of symmetry in physics. I'll take up the first point about epistemology now, and return to symmetry at the end.

Science is evidence-based reasoning that must test its concepts against reality. For a concept to have *scientific* meaning, its inferences must be observable, at least in principle. Descartes and Newton visualized time as something that exists *of itself*. To the absolutists, time just sits out there, waiting for us to discover it. Leibniz said: that's nonsense. You can't observe this time, just sitting out there all by itself, so why talk about it? Time is not a tangible entity independent of everything else.

Newton had to admit that, in practice, one could not refer motions to absolute space and absolute time, so therefore one had to *choose* a reference frame, a coordinate system. He said in the *Principia*:[7]

But because the parts of space cannot be seen, or distinguished from one another by our senses, therefore in their stead we use sensible measures of them...from any body considered as immovable, we define all places; and then with respect to such places, we estimate all motions...and so, instead of absolute places and motions, we use relative ones...

In his famous thought experiment about the rotating bucket, Newton thought he had evidence for the existence of *acceleration* relative to absolute space, but even that was arguable, as Ernst Mach later pointed out. But although Newton had to confess that *velocity* relative to absolute space could not be observed, he still granted absolute space and time a kind of Platonic reality:

...in philosophical disquisitions, we ought to abstract from our senses, and consider things themselves, distinct from what are only sensible measures of them...

On this point, Mach suggested that Newton had departed from physics and wandered into metaphysics.[8] At the end of the nineteenth century Mach observed (with the emphasis as in the original):

It would appear as though Newton in the remarks here cited still stood under the influence of the mediaeval philosophy, as though he had grown unfaithful to his resolve to investigate only actual facts. When we say a thing, A, changes with the time, we mean simply that the conditions that determine the thing, A, depend on the conditions that determine another thing, B,....but we may compare it with any other thing...[and] the illusory notion easily arises that all the things with which we compare it are unessential...Time, accordingly, appears to be some particular and independent thing, on the progress of which the position of [a] pendulum depends...

But...It is utterly beyond our power to measure the changes of things by time. Quite the contrary, time is an abstraction, at which we arrive by means of the changes of things;... A motion may, with respect to another motion, be uniform. But the question whether a motion is in itself uniform, is senseless. With just as little justice, also, may we speak of an "absolute time—" of a time independent of change. This absolute time can be measured by comparison with no motion; it has therefore neither a practical nor a scientific value, and no one is justified in saying that he knows aught about it. It is an idle metaphysical conception...

In Newtonian relativity, the absolute time to be *measured* by a clock was thought to exist *independent* of any clock. Time sat out there all by itself, running along at the same rate for everybody, whether they do physics in the Lab Frame or in the Rocket Frame. But according to critics such as Leibniz and Mach, clocks do not measure a pre-existing time; in a profound sense *they create* time. Time, *of itself*, does not exist; it comes into being only when there is some mark or difference whereby one can note a change. Besides counting periods of oscillations, I suppose we could use the entropy increase of the universe as a crude kind of clock, and in a real sense we use the expansion of the universe as a cosmic clock for any co-moving observer. But the entropy clock illustrates the point: when the universe finally reaches a state of thermodynamic equilibrium, no spontaneous processes will occur, nothing will change, and time will cease to exist.

But let's get back to Newton: to do mechanics, he had to make *some* statement about relativity. Theories of relativity are built on what remains *invariant* between members of a class of suitably defined reference frames, and Newton had to hang his theory of relativity on *something*. So he took the only path he really could under the circumstances, and made time and space separate relativistic invariants. There was simply no reasonable alternative, given the contemporary state of knowledge. Non-Euclidian geometry and the invariance of the speed of light lay far in Newton's future light cone. I think it's to Newton's credit that he was quite aware of the assumptions he made about space and time, and had the presence of mind to articulate them as such explicitly.

Sometime between 1895 and 1905, Albert Einstein began asking himself some questions about space and time and motion. As you know, those questions led to the Special Theory of Relativity. It's interesting to reflect that Einstein did not create Special Relativity by taking a "position" in the old philosophical arguments about whether space and time are absolute or relative. Indeed, when delivering the Stafford Lectures at Princeton University in 1921, Einstein commented that[9]

The only justification for our concepts and system of concepts is that they serve to represent the complex of our experiences; beyond this they have no legitimacy. I am convinced that the philosophers have had a harmful effect upon the progress of scientific thinking in removing certain fundamental concepts from the domain of empiricism, where they are under our control, to the intangible heights of the a priori. For even if it should appear that the universe of ideas cannot be deduced from experience by logical means, but is, in a sense, a creation of the human mind, without which no science is possible, nevertheless this universe of ideas is just as little independent of the nature of our experiences as clothes are of the form of the human body. This is particularly true of our concepts of time and space, which physicists have been obliged by the facts to bring down from the Olympus of the a priori in order to adjust them and put them in a serviceable condition.

Rather than arguing philosophically, Einstein asked how one *actually measures* the time interval between two separated events and the length of a moving object.

At age 16, Einstein began asking one of those profound kinds of questions that most second-graders—but only a few adult minds, like Einstein's—have the audacity to ask. He wondered what he would see if he rode on a beam of light. He later recalled:[10]

If I pursue a beam of light with the velocity c, I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, whether on the basis of experience or according to Maxwell's equations. From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest...

Einstein recognized in his simple question a deep paradox, which is one of Nature's ways of telling us that we are overlooking something important. Something was amiss here. So Einstein revisited Newton's assumptions about the separate invariance of time and space. That time intervals are *not* an invariant became quite apparent with a simple thought experiment.

Jacob Bronowski beautifully illustrated the crucial thought experiment as follows.[11] If I ride on the beam of light that was reflected from the clock tower when the clock read high noon, then I am always *riding along with the information* that says "The time is 12 o'clock." For me, and my beam of light, *no time advances* between the event of my interaction with the clock face, and the event of my interaction with the retina of the viewer's eye. But for the pedestrian who glances at the clock, the scattering of the light from the clock face, and the arrival of that same light in the eye, are separated by a nonzero increment of time. Absolute, invariant time—time that stands outside of events—does not exist.

This crucial insight about time came when Einstein realized that the relativity of time is ultimately the relativity of simultaneity. In the celebrated 1905 paper, *On the Electrodynamics of Moving Bodies*, he observed:[12]

It we want to describe the motion of a particle, we give the values of its coordinates as functions of time. However, we must keep in mind that a mathematical description of this kind only has physical meaning if we are already clear as to what we understand here by 'time.' We have to bear in mind that all our judgments involving time are always judgments about simultaneous events. If, for example, I say that 'the train arrives here at 7 o'clock,' that means, more or less, 'the pointing of the small hand of my watch to 7 and the arrival of the train are simultaneous events.'

He then proceeded to turn relativity on its head. In Newton's relativity, time and space intervals are separately invariant; therefore the speed of light is relative to the observer. In Einstein's relativity, the speed of light is invariant, and therefore the length of an object, and the time between two events, are not properties of the objects and events themselves. Rather, length and time are properties of the *relation* between the observer and the observed. Absolute time was out. Absolute space was out. Today we understand space and time through the invariance of the Spacetime Interval. In September 1908 the mathematician Hermann Minkowski began a speech with this now-famous introduction: [13]

The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.

He then proceeded to lay out what we today call "spacetime," a four-dimensional pseudo- Riemannian manifold with time as one of its dimensions. But let me return now to the second important point for physics that Leibniz raised in his criticism of absolute space and time. You will recall that he said, [6]

Supposing any one should ask, why God did not create everything a year sooner...There is no mark or difference, whereby it would be possible to know, that the world was created sooner...

Here Leibniz invokes a symmetry argument, in this case the system's invariance under a time translation. Similarly, in criticizing absolute space he invoked invariance under spatial translations and rotations. Such symmetries would prove to have profound consequences. The most comprehensive expression of the relation between symmetries and conservation laws was expressed in the elegant 1918 theorem of Emmy Nöether.[14]

In its deepest theoretical orchestrations, physics describes its task as maximizing or minimizing certain functionals, and considering these functionals' invariances under various transformations of the independent and dependent coordinates. Whenever a functional is invariant under a transformation *and* has been made an extremal, then Nöether's Theorem gives us an elegant conservation law: the conserved quantity is a linear combination of the

Hamiltonian and canonical momenta, with coefficients that are generators of the transformation. What then are some of the essential functionals in physics?

Ray optics was placed on a theoretical foundation in 1662 with Fermat’s Principle. It says that if a light ray goes from point A to point B, of all possible paths available to the ray, the path *actually* followed is the one that minimizes the time for the trip.

After Newton’s generation, it was realized that mechanics could also be expressed in functional language, called Hamilton’s Principle or the Principle of Least Action. Of all the trajectories in phase space available to a particle in going from event A to event B, the trajectory *actually* followed is the one that makes the time integral of the difference between the kinetic and potential energies a minimum.

Special and General Relativity can be expressed as a relativistic version of Fermat’s Principle: of all the trajectories between two events that are available to a freely-falling particle, the trajectory *actually* followed is the one for which the *proper time*, in other words the Spacetime Interval, is a maximum. It is significant that, in the weak-field and low-speed limit, the Relativistic Fermat’s Principle becomes Hamilton’s Principle.

I use these three examples—Fermat’s Principle, Hamilton’s Principle, and the Relativistic Fermat’s Principle—to point out the central role played by time as an independent variable, in these the most fundamental physics principles that we know. The task of physics, ultimately, is to describe how systems evolve with time. Time sits at the center of it all. With Augustine, we have to ask all over again, “What, then, is time?”

Let’s think about what we are doing when we do physics. Physics is the art of creating and testing and improving a network of *concepts* in terms of which the universe becomes comprehensible. For facts to be turned into knowledge, they have to be organized. That takes creativity, a system of values, and imagination.

Absolute time, sitting out there all by itself, was not a *thing* to be found because as such it does not exist. Time somehow comes into existence with change *in nature*, but time is also a *concept* we have created in terms of which the universe starts making some sense. We have gone far beyond the arguments of Descartes and Newton and Leibniz, and worry today about questions such as what happened before the Big Bang and whether time is quantized at the Planck scale.

One fact is quite clear however: We do not *really understand* space and time. It is therefore with some sense of humility that from this essay the “Elegant Connections” column will segue over the next four or five issues into a little history of what became big bang cosmology, including the story of the infernal cosmological constant.

But here is one fact about time of which I am fairly confident: Whatever time is—or is not—I see that I have exhausted my allotment of it today.

The time is gone, the song is over,
Thought I’d something more to say.”[18]

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References

[1] Johann Gottfried Herder (1744-1803), “Das Leben” forms the opening stanza of “Amor und Psyche.” In the original it reads,

Ein Taum, ein Traum is unser leben
Auf Erden hier.
Wie Schatten aud den Wogen schweben
Und schwinden wir.
Und messen unsre trägen Tritte
Nach Raum und Zeit.
Und sind (und wissen=s nicht) in Mitte
Der Ewigkeit.

My source was *First German Reader*, H. Steinhauer, Ed. (Bantam, 1972).
[2] Benjamin Franklin’s *Poor Richard’s Almanac* was published 1732-1757. Franklin collected Poor Richard’s sayings in *The Way to Wealth* (1757), under the guise of a sermon.
[3] St. Augustine, “Questions about Time,” from *Problems in Space and Time*, J. J. C. Smart, Ed. (Macmillan, 1973).
[4] René Descartes, “Space and Matter,” Ref. 3.
[5] Isaac Newton, *Mathematical Principles of Natural Philosophy*, Vol. 1, Florian Cajori Edition., translated by Andrew Motte, 1729 (Greenwood Press, 1962).
[6] Gottfried Leibniz, “The Relational Theory of Space and Time,” from the anthology of Ref. 3.
[7] Newton, Ref. 5.
[8] Ernst Mach, *The Science of Mechanics: A Critical and Historical Account of its Development* (Open Court, 1919).
[9] Albert Einstein, *The Meaning of Relativity* (Princeton University Press, 1922; 5th Ed. 1984).
[10] Albert Einstein, AAutobiographical Notes,@ in *Albert Einstein, Philosopher-Scientist*, Paul A. Schlipp, Ed., Vol. 1 (Harper & Row, 1959).
[11] Jacob Bronowski, *The Ascent of Man* (Little, Brown, & Co., 1973).
[12] Albert Einstein, “On the Electrodynamics of Moving Bodies,” originally published in *Annalen der Physik* 17 (1905), 891-921. The present translation from *Einstein’s Miraculous Year: Five Papers That Changed the Face of Physics*, John Stachel, Ed. (Princeton University Press, 1998).
[13] Hermann Minkowski, ASpace and Time,@ anthology of Ref. 3.
[14] Emmy Nöether, “Invariante variationsprobleme,” *Nachr. Akad. Wiss. Göttingen, Math-Phys. K1. II*, 1918; translation by M. Tavel, “Invariant variations problems,” *Transp. Theory Stat. Phys.* 1, 186-207 (1971).
[15] Pink Floyd, “Time,” from the *Dark Side of the Moon*.