WHY IS *c* A COSMIC SPEED LIMIT?

Dan Bruiger, May 2023

Abstract: The Lorentz transformations can be interpreted either in ontological or epistemic terms. The invariance of *c* could have a different interpretation, as a side-effect of the exclusive role of light as signal between frames of reference. It would not necessarily pose an absolute cosmic speed limit. Time dilation would have a different explanation.

I. Ontic and epistemic approaches

Science faces the same epistemic problem as ordinary experience: how to distinguish appearance from reality. *Appearance* is largely visual and from a distance. Apparent motion involves measurable apparent change in size or position and their time derivatives. Measuring the reality that gives rise to the appearance, on the other hand, implies a causal interaction of the observing and observed systems. The property relevant to that interaction is *mass*, which can be measured directly by weighing, if at rest nearby. But it can also be measured indirectly through changes in apparent movement of distant things. An approach that emphasizes ontology more than epistemology may fail to specify how quantities such as mass are to be measured—that is, by weighing in the rest frame or by observing changes of position from a distance while moving.

To measure anything not in your immediate proximity requires a reference frame that imaginatively extends from your locality to that object. It also presumes some way to gather that information from a distance, which is mainly light. To preserve an epistemic approach requires keeping in mind the direct relation of the object to the observer as well as the object's relation to the frame of reference. In the case of distant moving things, that direct relation involves their movement toward or away from the observer, as distinguished from motion in relation to the frame of reference. The challenge to track distant moving things using signals of finite speed underlay the crisis in physics that occurred toward the close of the 19th century. In the case of distant moving bodies, concepts of force and mass cannot be separated from apparent motion.[1]

II. Mass and acceleration

Acceleration is a key concept in dynamics. It did not occur to the ancients, who had a notion of force derived from muscular assertion, which they did not associate with change of speed or direction. It was problematic for the early scientists too, who recognized that "force" is proportional to both mass and acceleration, thus entangling those concepts. This gave rise to circularity in the mutual definition of force and mass (in the formula $f=ma$), and in the concept of inertia or momentum (mv).[2] Such confusion led to a dispute between Leibniz and Newton over what would later become the concept of energy or work.[3]

While force could be directly *felt* through bodily contact with objects, with respect to distant things it could be assessed only through visually observing changes of motion. Thus, there are two distinct modes for observing force (and hence mass). Moreover, force is felt in the effort required to

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[1] Barbour 1989 *Absolute or Relative Motion? Vol. 1: The Discovery of Dynamics*. Cambridge University Press, Cambridge (1989)]

[2] Newton's first law *presumes* the absence of outside forces; but, circularly, outside forces are *defined* as violations of the first law.

[3] The modern view is that a system of colliding bodies preserves overall momentum but not necessarily overall kinetic energy, part of which can be transformed into some form of internal energy, for example heat.

lift objects, including one's own body. Yet, it is also felt in the effort to make a stationary object move or to slow down a moving one. Thus, there are also two distinct concepts of "mass" as the measure of the amount of matter involved: gravitational mass (weight) and inertial mass.

As a line-of-sight visual effect strictly between two observers, acceleration (like velocity) is mutual.[4] That is, each observer would perceive the other as accelerating toward or away by the same amount. However, acceleration as *felt* could be different for the two observers. Whatever is responsible for this difference suggests an absolute reference frame. The observer who *feels* a force is the one who is "really" accelerating, whereas the one who feels no such force is the one "at rest" in that frame. (Of course, they could *both* be accelerating.)

What could account for the real existence of an absolute rest frame and the consequent feeling of being accelerated with respect to it? This was the big question that Mach had pondered. His answer was that it must (somehow) be all the other matter in the universe! Since the stars are comparatively far from the observer, their motions with respect to each other appear minimal. The "fixed" stars, then, approximate an absolute frame of reference. While motion of two observers relative to each other is perceived in a mutual way, their motions perceived relative to the stars can differ.[5] Yet, Mach's insight does not really tell us why change of velocity with respect to the bulk of the universe is felt as force while constant velocity with respect to it is not. Why is acceleration special, and what is mass that it should be entangled with it?

III. The problem of the ether

The Michelson-Morley experiment precipitated a crisis in physics but did not definitively settle the issue of the ether. The Special Relativity (SR) rendered the ether superfluous but Einstein himself admitted that it did not disprove it. Later experiments seemed to confirm the null result, but such results were sometimes contested. Experiments continue to be proposed to detect motion relative to a cosmic frame at rest.[6] The persistence of such efforts reflects the common-sense notion of an absolute perspective, a major thread in ontological thought. A more epistemic approach proposes that only motion relative to identifiable things can be measured. That could be motion in direct relation to the observer (approaching or receding) or it could be in relation to some other visible landmark or background (but not to an imaginary frame of reference). Either way involves light or some other messenger arriving to the observer from a physical source.

Supposing light to consist of waves, the problem with the ether as a medium is that (unlike the ocean or the air) it is not itself a perceptible thing. The alternative assumption—that light consists of *particles* moving in empty space—requires no medium in which to travel. The corresponding problem, however, is that a particle of light is no more a perceptible object than is the ether. By what means could one see a photon? Light is the *means of seeing* for us as visual creatures—not a

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[4] Direct visual evidence for such mutual acceleration in the line of sight would be a changing rate of change in apparent size; but the human visual system is not very good at estimating it. Indirectly it could be measured as changing frequency of the light (Doppler effect for acceleration).

[5] A clock could be set by referring to (distant) astronomical events, such as the periods of binary stars or quasars. A second clock in the same reference frame could be set by referring to local atomic events, such as frequencies in atomic clocks. For an observer at rest with respect to the stars, time measured by these two clocks should coincide, though not for an observer who moves relative to the "absolute" frame represented by the stars.

[6] For example: Donald C. Chang "Is there a resting frame in the universe? A proposed experimental test based on a precise measurement of particle mass" Eur. Phys. J. Plus (2017) 132: 140. The idea is to use particles with mass rather than light in an equivalent of the MM experiment, using mass spectrometers to detect absolute motion of the laboratory through the "vacuum."

visible object.[7] The objectification of light as either particle or wave leads to paradox. Whatever its nature, light is used by observers as a *signal* connecting them with each other and with objects. The fact that light is not a *thing* but a *coupling between observers*, or between emitters and absorbers, calls into question the very meaning of the intervening space!

Desperate attempts were made to salvage common sense in the wake of the MM experiment. Fitzgerald, and Lorentz himself, proposed that the rigid arms of the interferometer were not in fact rigid. After all, solid matter is essentially regulated by electromagnetic forces between atoms, whose spacing might be affected by motion through the ether: the space between electrons, if not the electrons themselves, might be distorted by such motion. Alternatively, it was proposed that the ether was partially dragged along with the earth in its orbit, so that there was no local motion with respect to it.

Such attempted solutions were ontological. The Special Theory of Relativity (as Einstein's 1905 paper came to be known) took a different tack. It has two parts: "kinematic" and "electrodynamic." Their inclusion together may reflect Einstein's deep struggles with the issues involved.[8] At heart, SR presents a theory of invariance: a way to express the laws of physics in the same form for all observers. That meant preserving the relativity of observation (which encompasses the addition of velocities); but also preserving the speed of light as a "law" of physics (as per Maxwell's theory), which should thus be the same for all observers. To all appearances, these requirements were in contradiction.

Einstein's quest to reconcile them began with a youthful thought experiment: what would it be like to chase a beam of light? In his own words, recollected long after: "If I pursue a beam of light with the velocity c… I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating. There seems to be no such thing, however, neither on the basis of experience nor 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. *For how [else] should the first observer know, or be able to determine, that he is in a state of fast uniform motion?*"[9] I put the last sentence in italics to emphasize the tacit implication that *light itself* is the means to determine the (constant) state of motion, which cannot be *felt* in an inertial system. How would light ever reach an observer moving with the speed of light away from its source? How, then, could one even gauge one's speed, to *know* that one is moving at *c*? Mulling over this paradox for a decade led Einstein to the kinematic part of SR. To quote him again: "An analysis of the concept of time was my solution. Time cannot be absolutely defined, and there is an inseparable relation between time and signal velocity."[10] He does not elaborate there on that relationship, emphasizing instead the challenge to overcome the absolute character of time; however, he could as well have emphasized the circular mutual dependence of light and measures of time.

SR rests on two notions "only apparently irreconcilable": (1) "the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold

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[7] Steven M. Rosen "Why Natural Science Needs Phenomenological Philosophy" *Progress in Biophysics and Molecular Biology* 119 (2015: 257–269): "instead of lending itself to being treated as an object open to the scrutiny of a subject that stands apart from it [light] must be understood as entailing the inseparable blending of subject and object."

[8] Robert Rynasiewicz "The optics and electrodynamics of 'On the Electrodynamics of Moving Bodies'" Ann. Phys. (Leipzig) 14, Supplement, 38 – 57 (2005), p39: "The problems [with Maxwell's theory] addressed in the Electrodynamical Part drove Einstein, albeit in round about ways, to the discovery of the self-standing doctrine as set out in the Kinematical Part. This doctrine yielded a secure and independent justification, previously lacking, for the approach he had explored for the problems of the Electrodynamical Part."

[9] A. Einstein *Autobiographical Notes*, translated and edited by P.A. Schilpp (Open Court, LaSalle, 1979), pp.48–51. [my italics]

[10] Einstein, "Kyoto lecture"

good;"[11] and (2) "light is always propagated in empty space with a definite velocity *c* which is independent of the state of motion of the emitting body."[12] Einstein cuts the Gordian knot by boldly offering these as "postulates," to be accepted axiomatically. His presentation then has the flavor of a logical deduction from first principles—reasoning that may be consistent with data but does not depend on it. As a reviewer at the time commented, the light postulate is the more remarkable, since its strange consequences "offer the only method of preserving the science of mechanics substantially in its present form."[13] Indeed, that was Einstein's goal. Despite his early positivism, it was his lifelong concern to preserve the objectivity, rationality and consistency of physics, the principle challenges to which were the dilemmas that gave birth to the two great revolutions, relativity and quantum theory. His solutions involved taking the observer into account, but with an aim to preserve an essentially observer-independent worldview—the fundamental stance of classical physics.

The argument in SR begins with an inquiry into the concept of simultaneity—what in fact it means to establish the timing of an event. The space and time coordinates of an event will not be the same in two frames of reference moving uniformly with respect to each other, either of which is equally entitled to consider itself "at rest" and the other "moving." Based on his two postulates, Einstein proceeds to derive the mathematical transformations from the stationary to the moving coordinate system—or vice-versa.[14] While coordinates may differ, the *transformations* between them will be the same for both observers, on the premise that the speed of light is the same for all.[15] In SR, Einstein resolved the dilemma posed by the intermediary of light in such a way that the classical worldview could be maintained. Ironically, however, the relativity of space and time (their duality and epistemic contingency) was overcome in a new ontological entity replacing the ether: the space-time continuum.[16]

SR debunked an absolute frame of reference provided by the electromagnetic ether. Could there still be some other basis for an absolute rest frame? Post-relativity, the "spacetime manifold" took the conceptual place for physicists of the luminiferous ether. All fields were then construed as states of the manifold, which effectively stood in for the ether.[17] The manifold employs a space-time interval, with the speed of light built into it, rather than a space interval *through* time. By definition, this interval is invariant among observers in different reference frames. However, it cannot be

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[11] The so-called principle of relativity, more accurately the principle of invariance or co-variance.
[12] The so-called "light postulate." (Note that nothing is said of the state of motion of the receiving body.)
[13] Gilbert N. Lewis and Richard C. Tolman (1909) "The Principle of Relativity and Non-Newtonian Mechanics"
[14] These equations had earlier been adduced by Lorentz in his (ontological) theory of electrodynamics. Poincaré had also found them on similar grounds. Einstein's approach in the kinematic part was novel because it was epistemic rather than ontological.
[15] It is no coincidence that his papers on the photoelectric effect and SR were published the same year. [Harvey R. Brown *op cit*, p70ff.] SR draws indirectly on Einstein's ideas about the particle nature of light—the other thing mulling in the back of his mind while thinking about "electrodynamics." The idea that light could emanate outward in all directions like an expanding wave, yet be absorbed in a definite location as a definite amount of energy, led Einstein to consider an emission theory of light, with photons more like bullets than waves. (That circumvented the problem of the ether, but not the addition of velocities and the apparent invariance of *c*.) In SR, the physical nature of light is set aside in favor of its role as a signal. This is the solution I call epistemic rather than ontological. It avoided questions about what happens physically in reflections, for example, and also the problem that strict rigidity of physical rods would be outlawed by SR itself, since it implies faster than light transmission of forces. See: Robert Rynasiewicz "The optics and electrodynamics of 'On the Electrodynamics of Moving Bodies'" Ann. Phys. (Leipzig) **14**, Supplement, 38 – 57 (20)
[16] "The view that the *space-time manifold* is a substratum or bedrock…is just the twentieth-century version of the ether hypothesis." Harvey R. Brown *Physical Relativity*: *Space-time Structure from a Dynamical Perspective* Oxford UP, 2005, p67]
[17] John Earman, quoted in HRB, p67

measured. The space-time interval can only be *calculated*, using the Pythagorean theorem, on the basis of space and time intervals separately measured. Except for light signals, no measuring tool exists that is a hybrid of a ruler and a clock![18] But to *define* light as the measure of this interval is circular reasoning, since the speed of light itself is defined in ordinary units of space and time. The *mathematical* advantage of space-time is that certain physical concepts can be treated more conveniently than by dealing with space and time separately. To reify this mathematical convenience, however, is a metaphysical act rather than a revelation of truth. Quite the contrary, it masks the truth of the observer's epistemic dependency on light.

IV. Length contraction and time dilation

In ordinary experience, light is virtually instantaneous. The effects of finite *c* become appreciable only when considering spatially separated observers moving relatively to each other with a speed nearing that of light. These effects are still described as "length contraction" and "time dilation," as though they are physical changes in the objects themselves, not a result of the epistemic circumstance of the observer using light as a signal. However, physical changes require a causal explanation, which is a unilateral effect. In the case of distant moving objects, that must mean an interaction either with the observer's apparatus or with the intervening space or medium (i.e., the ether).

A causal (ontological) explanation is belied by the fact that the above measurable effects are *mutual*. With equal justification both observers perceive the *other's* measuring rod to have shrunk and clock to have slowed down. These effects involve a line-of-sight component for observers in relative motion. The kinematic part of SR sidesteps any question of changes in the "real" physical shape and size of moving objects. The arguments of SR were first presented there in terms of mutual line-of-sight ("longitudinal") effects. Since the contraction effect is mutually perceivable, it cannot be objectively physical in the sense that there can be agreement about which observer's measuring stick has "really" shrunk. On the other hand, toward the end of the "kinematic" part of his paper, Einstein develops a conclusion that implies time "really" slows down, in an asymmetric way. This has since become known as the "Twins Paradox." His argument there implies an ontological interpretation of time dilation. Indeed, there *is* empirical evidence for the reality of time dilation, but its explanation may lie outside situations addressed by SR—namely, situations involving acceleration or the presence of a gravitational field, as considered in General Relativity. However, the arguments for general relativistic effects (time dilation because of acceleration or gravity) seem to have been derived by Einstein from SR. In view of that circularity, time dilation remains a concept that is ambiguous and inadequately expounded.

Should length contraction and time dilation in SR be understood epistemically or ontologically? If it were the case that motion through "space" (whether with uniform velocity or accelerated) could produce objective ontological effects, there must be some objective interaction (with space) that causes these effects. In other words, we come full circle to the problem of the ether![19] The kinematic part of Einstein's paper implies an epistemic interpretation, though not consistently; his argument in the electrodynamic part is couched in ontological terms, but proceeds with a parallel logic as in the kinematic part. Einstein did little in the paper or after to clarify the distinction—

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[18] Brown gives the example of the *waywiser* as a clocklike device that measures distance. As he points out, there is no analogous mechanism to read off four-dimensional distances. There is no traction with space-time. Light itself is the only such device. [Harvey R. Brown *op cit*, p8]

[19] That we are not done with the ether is shown also by modern theories of the "vacuum," and the attempt to explain inertia as an interaction with the Higgs field.

hoping, perhaps, to have it both ways.[20] Others, beginning with Lorentz and Fitzgerald, certainly took the ontological interpretation seriously. Pauli did not think the attempt to explain the Lorentz contraction at the atomic level should be abandoned, but seemed to embrace both interpretations.[21] Over the years, Eddington changed his mind about length contraction, at first presenting it as epistemic, later as a result of the behavior of electrical forces.[22] The curious relationship between the kinematic and electrodynamic parts of Einstein's original paper mirrors the confusing relationship between epistemic and ontic points of view.

V. The cosmic speed limit

A consequence of SR is that the speed of light in empty space cannot be exceeded by any physically real entity, whether matter or radiation.[23] Einstein's explanation in the kinematic part is that length in the direction of relative motion shrinks to zero as v approaches c. In the electrodynamic part, it is that the kinetic energy of an object grows to infinity as its v approaches c. In both cases, what is involved is the changed *appearance*, in one frame of reference, of something moving with respect to it, whose appearance would be "normal" in its own frame of reference. If these effects are not mere appearance, they should be independent of any particular means of signaling and not mutually perceived.

Why is c a cosmic speed limit? An *epistemic* answer is that the apparent limit is the result of the unique role of light as a yardstick for observers. From that point of view, it is a logical (if not physical) possibility that there could exist a supraliminal carrier of information we could potentially use instead.[24] It would take the place of light as our epistemic vehicle, and *its* speed would replace that of light as the cosmic speed limit. Light would then take a place with sound as a *phenomenon to observe* rather than the *means of observing*.[25] Conversely, if we could *only* use sound to observe

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[20] For example: "The kinematic shape of a body undergoing uniform translational motion… differs from its geometric shape only by a contraction in the direction of the relative motion…" [Einstein Doc47 "The Relativity Principle"]

[21] "The contraction of a measuring rod is not an elementary but *a very complicated process*. It would not take place except for the covariance with respect to the Lorentz group of the basic equations of electron theory, *as well as* of those laws, as yet unknown to us, which determine the cohesion of the electron itself." [Pauli, quoted in HRB, p118—italics added] The covariance of the basic equations of electron theory is what Einstein presented, in the kinematic part, as epistemic. The cohesion of the electron itself suggests an ontological interpretation.

[22] HRB p119.

[23] Thomson in 1893 had proposed that c is a cosmic speed limit on electrodynamic grounds: "When in the limit… a charged sphere moving with the velocity of light behaves as if its mass were infinite, its velocity therefore will remain constant, in other words it is impossible to increase the velocity of a charged body moving through the dielectric beyond that of light." [J. J. Thomson, *Notes on Recent Researches in Electricity and Magnetism*, Oxford Clarendon, 1893, p21]

[24] The faster-than-light entity would have to replace light as our principle means of investigation. Otherwise it would give rise to the classic paradox that a supraliminal signal could be received before it was sent. That paradox would arise, however, only if conventional light continues to be the standard, the measuring stick for all phenomena including supraluminal signals.

[25] Since we are engaging in wild counterfactuals, perhaps this would enable us to perceive photons or the medium in which light travels, both of which are presently invisible to us.

the world, *it* would constitute the limiting speed.[26] We know (through light) that things can move faster than sound. But—absent light—how would we know this using only sound itself?[27]

An *ontological* answer concerning the cosmic speed limit implies some real interaction with an ether, such that inertia increases objectively because of motion through it (like moving through molasses). If all types of particles and radiation were wave-like excitations of some single medium, there would be a physical basis for understanding the difference between massive and massless particles—and for why no massive particle can move faster than *c*. The cosmic speed limit would be determined by the properties of that medium, as the speed of light is determined in Maxwell's theory by the properties of the electromagnetic field.[28] It would *be* the ether.[29]

VI. Conclusion

Einstein's contemporaries (Lorentz, FitzGerald, Larmor, Poincaré) explained the MM result in ontological terms, as the interaction of material bodies with the ether. Length contraction and slowing of clocks were interpreted as "real" changes due to electrical forces between or within atoms. Ultimately, Einstein also proposed an ontological explanation. But it was to interpret these phenomena in terms of the malleable structure of space-time rather than the malleable structure of matter, casting doubt on the very distinction between matter and space-time.[30]

The Lorentz transformations could as well be interpreted in epistemic terms: of observers' mutually relative state of motion, given the finite intermediary of light. Space-time need not be treated as a new object (a metaphysical choice) if the observer and the medium of observation are fully taken into account as part of the system. The invariance of *c* would have a different interpretation, not as an absolute cosmic speed limit but as a side-effect of its exclusive role as signal between frames of reference. Time dilation would have a different explanation, as a function

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[26] Cf. Max Born: "As a matter of fact, if we use sound signals to regulate the clocks, Einstein's kinematics can be applied in its entirety to ships that move through motionless air. The symbol *c* would then denote the velocity of sound in all formulae… and the Lorentz transformations would hold between the system of measurement of the various ships… Is this the meaning of Einstein's theory? Certainly not! Rather it is assumed as self-evident that a measuring rod which is brought into one system of reference *S* and then into another *S'* under exactly the same physical conditions would represent the same length in each… the new kinematics is to be valid just when the *same* rod and the *same* clock are used first in system *S* and then in system *S'* to fix lengths and times." [Max Born *Einstein's Theory of Relativity* Dover, 1962, p251-2] But the point is precisely that the same instruments *cannot* be so used, first in terrestrial then non-terrestrial systems, at least not without involving some acceleration. In the ships analogy, we can board the various ships in succession with our standard ruler and clock, and verify that the relativistic effect using sound is illusory compared to measurement using light. This is not possible when we cannot board the remote moving system without accelerating and decelerating.

[27] A rocket or jet plane can travel faster than sound in air. Yet, sound signals reaching the ground from it would lag increasingly behind its real position, giving the false impression that it was *not* moving faster than sound. The phenomenon of the sonic boom could be a telltale clue that its source was moving faster than sound. There does not seem to exist a corresponding phenomenon for light, unless the mysterious Cherenkov radiation.

[28] See: Chang, D.C. (2018) A New Interpretation on the Non-Newtonian Properties of Particle Mass. Journal of Modern Physics, 9, p228-29

[29] If it is not identified with the electromagnetic field, there might exist unknown other fields with their own characteristic wave velocities, which might exceed *c.* If such a field could be used for perception or transmission of information, then there could exist a signal faster than *c*. On the other hand, if there is but one field, of which all others appear as manifestations, and if this one field happens to be characterized by the velocity of light, then no signal could be faster.

[30] Carlo Rovelli "Halfway through the woods: contemporary research on space and time" in John Earman and John D. Norton (eds) *The Cosmos of Science* U. of Pittsburg Press, 1997, p181

of moving things physically interacting with something we can refer to as an ether. The cosmic speed limit, *c*, is not an absolute or metaphysical principle, but an incidental property of the signals by means of which we perceive moving things. If we should ever discover a faster-than-light means of communicating, its velocity would become the new limiting speed and the new constant appearing in the Lorentz transformations and other fundamental equations.