There's No Such Thing as the Speed of Light

So What the Hell did Michelson Measure?!

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1 Introduction

Here are two statements that are both very plausibly true, but which seem to be in serious tension:

(1) In 1879 A. A. Michelson measured the speed of light to within 99% accuracy

(2) Strictly speaking, there is no speed of light in Special relativity.

The purpose of this paper will be to resolve the tension between (1) and (2). The majority of what follows will be devoted to defending the second claim, which is remarkably controversial even among working physicists and philosophers of science.

I argue that this controversy is due to a confusion about the role of co-ordinate representations in characterizing different theories of space-time. Once this confusion is resolved, it becomes clear that the claim that light has a speed at all is nothing more than an artifact of our representational scheme, and not an accurate reflection of the space-time structure of relativity. Before going into all that, I will say a few things in favor of (1).

1.1 Michelson Measured the Speed of Light

This is not a history of science paper, but it will behoove us to understand exactly what Michelson did and why that counts as a measurement of the speed of light. As a matter of historical fact, (1) isn't in dispute. A. A. Michelson really measured the speed of light in the late 1870s, and his result was $299,944$km/s(± 51). This result is only about 150km/s off from the currently accepted value of c: $299,792$km/s.

(1) In 1879 A. A. Michelson measured the speed of light to within 99% accuracy

The experiment works by associating an easily controllable and measurable quantity, in this case the rate of rotation of a small mirror, R, with the time it takes light to travel a round-trip along a certain path. In particular, the system made use of a pair of mirrors and a lens with very long focal length, L. So R, the smaller spinning mirror, reflects light coming from a slit, S, onto a larger mirror, M, at a great distance. The light reflects off of M, through L and is reflected by R back onto S. When R is spun at a high enough speed, the reflected light is deflected due to the motion of R during its travel to M and back, and so the light that arrives back at S doesn't line up perfectly with the original slit.

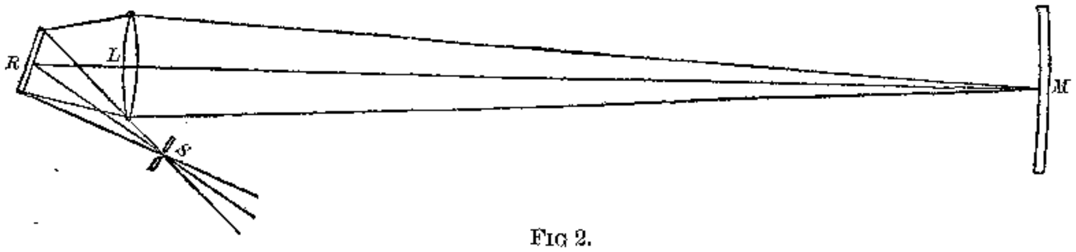

FIG 2.

Figure 1: A simplified diagram of Michelson's experimental setup, included in Michelson's 1880 paper.

Using this setup, Michelson was able to determine that the speed of light would have to travel at $299,944 \pm 51$km/s to explain the specific relationship between the rate of rotation, length of the light beam's route, and the measured amount of deflection. Since then, more precise measurements have been done, but this is a good example. Moreover, while Michelson was not completely accurate, the fact that he was close tells us two things. First, that there is a correct answer about what the speed of light is. And, second, that it's possible to be partially-incorrect about it (suggesting that it is not merely conventional).

1.2 Sketch of the Paper

This section introduced the tension between (1) and (2), and gave a general overview of the historical facts surrounding the truth of (1). Sections 2 and 3 are devoted to defending claim (2). Section 2 argues, specifically, that there is no absolute motion in special relativity (and, hence, no absolute speeds), and that the role that the trajectories of light rays play in a special relativistic world is incompatible with them standing in meaningful *relative* velocity relations.

Section 3 addresses the most common substantive argument in favor of there being a speed of light. According to this argument, light has a speed because all co-ordinatizations that describe inertial reference frames agree that light has a speed (and that it's c), even if they disagree about other things (like whether two space-like separated events are simultaneous). This line of reasoning comes from commitment to what I call a Co-ordinate Abstraction Principle. I show that this principle, in its most straightforward formulation, has clear counterexamples. Even further, I show that any reformulation of the principle weak enough to rule out these counterexamples will be rendered too weak to apply to the speed of light.

Once the plausible truth of (2) is established, Section 4 resolves the tension between (1) and (2). In some sense, the value of c as 299,792 km/s, is just a matter of our choices of spatial and temporal units. However, the speed of light cannot be purely conventional, or else it could not have been discovered. What Michelson measured was a real feature of the physical world, but it is neither a speed nor purely a matter of convention. The reasons our choices of spatial and temporal units give rise to an a posteriori discoverable fact is that the structure of Special Relativity makes independent units of temporal duration and spatial distance redundant. I explain why this value is so readily represented as a speed, and how Michelson's measurement could be tracking this property, despite it not being a speed at all.

2 Does Light Have a Speed?

How could there not be a speed of light in Special Relativity? Einstein (1905) explicitly mentions light and its speed as a foundational postulates of his physical theory. He says "light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body". How could it be that light doesn't have a speed?

To be able to answer the question "Does light have a speed in special relativity?" we need to understand what speeds are, and what the special theory of relativity says about the structure of the world. So what is a speed? This is a question that has had different answers at different times in the history of our physical theories, but there is a simple core concept. Speed is the rate of motion, and motion is the change in *position* over *time*.

That is to say, to travel a greater distance (greater change in position) in the same amount of time, or to travel the same distance in a shorter amount of time, one travels at a faster speed.

$$\text{Speed} = \frac{\text{Distance Traveled}}{\text{Time Elapsed}}$$

We'll see that that classical Newtonian mechanics will keep close to this core conception, but that things move further and further away as we move to more contemporary space-time theories.

2.1 Speed as a Defined Quantity: Newtonian Space and Time

In Newton's original formulation of his physical theory, he introduced two entities, Absolute Time and Absolute Space. Absolute space is a physical entity and the parts of space (i.e. spatial points and regions) have an ontology similar to that of material objects. Like material objects, points and regions of space persist through time. This means that, just as there's a fact about whether or not you're sitting in *the very same chair* as you were ten minutes ago, there's a fact about whether or not your chair is located in *the very same region* of absolute space as it was ten minutes ago.

In Newtonian absolute space and time, speed is a defined quantity. If an object has occupied *the same* spatial point over a certain span of time, then its speed is zero. If an object has moved at, e.g., a constant rate in a straight line and ended up 15 meters away from its starting position in space after three seconds have passed, then the object possessed a speed of five meters per second during that interval.[1] Newton's account very clearly matches our core conception of speed (and, arguably, is the originator of its modern formulation).

The structure of absolute space and time is what supports this definition. Absolute time allows us to ask how much time has elapsed between the start and end of the particle's trip. Absolute space allows us to ask about the distance between points in space at any given time, and, since space persists through time, there's a fact of the matter about the spatial distance between the where the object was at the start of the interval and where it is now.

2.2 Speed as a Primitive Quantity: Newtonian Space-Time

Some physical theories lack the theoretical underpinnings of absolute motion or absolute time difference. For such theories, if they are to admit of speeds, they must ground it in some other primitive (either taking motion itself to be primitive or intro-

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[1] Its velocity would consist of that speed, 5m/s, in the direction from the object's start position to its end position.

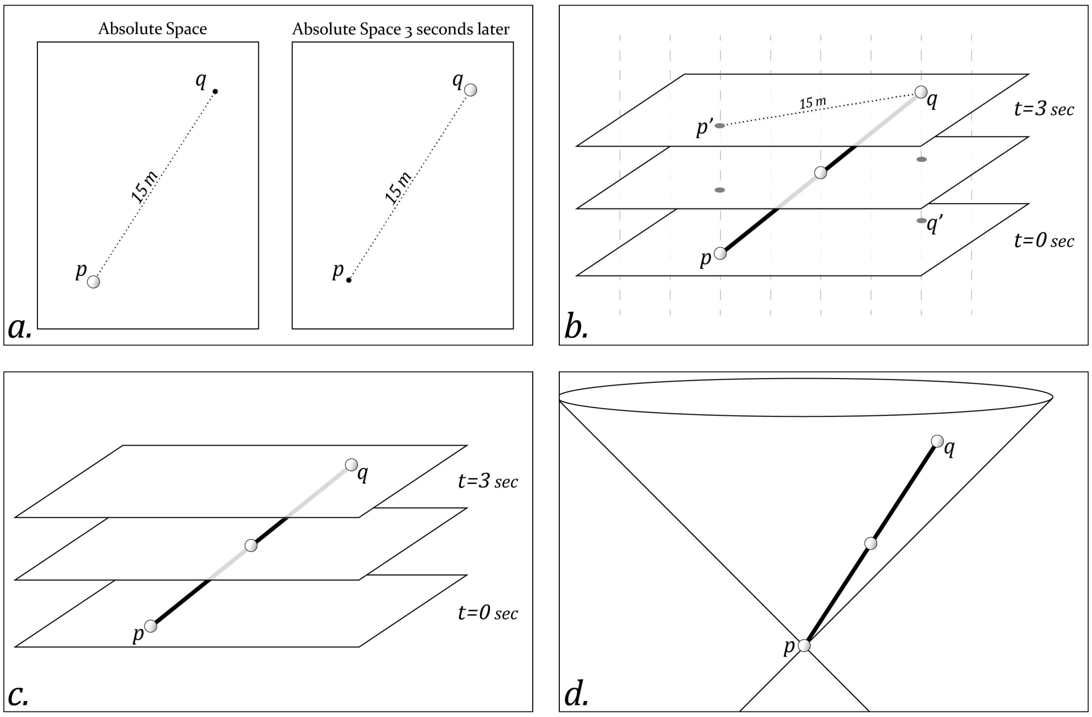

Figure 2: Four Space-time Diagrams, representing an object moving 15m in 3 seconds (where p is its starting point and q its ending point) as much as is possible using the space-time structures of: a. Newtonian Space and Time, b. Newtonian Space-time, c. Galilean Space-time, d. Minkowski Space-time.

ducing some other definition in terms of something other than absolute motion). For example, in Newtonian Space-time (a very different view than Newtonian Space *and* Time), the points in space are replaced by time-bound space-time points. While absolute space's points are occupied by point-sized objects, space-*time* points are occupied by point-sized and instantaneous *events*.

To include speed as an absolute quantity, we must add it in by hand. Specifically, we introduce *absolute rest* (i.e. an absolute speed of 0) as a primitive posit. In doing so, we designate certain trajectories as being "rest trajectories". Armed with this machinery, we can say that each space-time point at each time along one of these trajectories is located at the "same" position, even though they are numerically different points in space-time. Consider the contrast: in Newtonian Space and Time, if you start at one point in absolute space and remain at absolute rest for 1 second, you will occupy the very same point of absolute space 1 second later.

From this baseline, non-zero speeds can be defined using the global time elapsed between time-slices and the spatial distance between points within each slice. For example, suppose a particle is traveling from p to q (see Figure 2). While the space-time point, p, where it started its journey does not exist three seconds later, we *can* ask how far the object's final position is from the point of space-time which is *on the same rest trajectory* as p (like the point, $p\prime$, in figure 2). So if the distance between $p\prime$ and q point is 15m, then we can say the particle's speed was five meters per second.

2.3 No (Absolute) Speed: Galilean Space-Time

There are some physical theories that lack the capacity to define speeds in the normal way but also do not add any primitive ontology to capture it. These are theories in which (absolute) speed is, simply, *not a thing*. In Galilean Space-time (sometimes called Neo-Newtonian Space-time), the same space-time ontology as Newtonian Space-time exists, but no cross time "rest trajectories" are posited. Without those trajectories, the Galilean cannot define absolute rest (and, therefore absolute motion). How can we do physics on a space that lacks absolute motion? Two things help. First, Galilean Space-time is more than able to capture relative motions (relative motion being the change in spatial distance between bodies over time). Second, there's geometrical structure that allows Galilean space-time to to distinguish accelerated from inertial motion (where 'inertial' motion just means motion not subject to forces): the affine structure of the cross-time trajectories (i.e. which trajectories are straight vs. curved/bent).

We can group points of space-time into inertial (straight) trajectories. The old "rest trajectories" of Newtonian Space-time will all be straight trajectories, but there will be infinitely many others (corresponding to, by the Newtonian's lights, trajectories of uniform motion at the same speed in the same direction). But with only inertial trajectories we cannot define absolute speed, as that depends on being able to distinguish absolute rest from absolute uniform motion. For Galilean Space-time, this is a feature, not a bug. It allows the Galilean to capture the facts about whether a body is accelerating or not (inertial/straight trajectories are unaccelerated, and any bend or curve away from a straight trajectory is an acceleration), meaning that it can give the correct predictions for inertial effects (like the water in a spinning bucket) without being committed to the existence of absolute rest (like the two previous space-time theories are).

As Figure 2 demonstrates, there is not enough structure in Galilean space-time to represent the particle moving from p to q as having an absolute speed of any kind.

Referring back to our core conception of speed as “distance traveled/time elapsed”, we see that Galilean space-time retains a global sense of time elapsed, but lacks the cross-time distance structure necessary to be able to say the object moving from p to q traveled 15m.

2.4 Minkowski Space-time and a Simple Argument

Now we can turn to the Special Theory of Relativity (or STR). The space-time of special relativity is known as “Minkowski Space-time”. I described Galilean Space-time, above, because Minkowski Space-time is a close relative of Galilean Space-time and, while there are some big differences between them, Minkowski Space-time neither brings back temporally persisting spatial points nor does it reintroduce absolute rest trajectories. In fact, it’s even less equipped to define up absolute motion than Galilean Space-time. Since Minkowski Space-time also does away with *global time difference* since it does away with *absolute simultaneity*. Every point in Minkowski space-time has a light-cone consisting of the trajectories (towards the future) that light rays released at that point would follow, as well as light trajectories from the past converging on that point. If x is not inside of a space-time point’s light-cone, then we say that those two points are at “space-like separation”. For a pair of space-like separated points, there’s no fact of the matter whether the two are simultaneous, or if one occurs before the other (or vice versa). Recall that absolute speed in Newtonian Space-time requires both absolute rest trajectories *plus* the ability to compare distances between spatially separated points on the same time-slice (aka two simultaneous points). With neither absolute rest nor absolute simultaneity for space-like separated points, absolute speed is looking dead in the water.

This means that nothing in Special Relativity (under the normal way we interpret that theory) has an absolute speed. Hence, light does not have a speed. So our argument for (2), recall:

(2) Strictly speaking, there is no speed of light in Special relativity.

is a simple case of universal generalization: Everything in the Special Theory of Relativity is such that it doesn’t have an absolute speed. Light is one of the things in the Special Theory of Relativity. Therefore, light doesn’t have an absolute speed.

What if Light's Speed isn't Absolute?

Before we move on, let's consider a bad way to try to resist this argument. One might try to point out that I've only shown that light doesn't have an *absolute* speed, not that it doesn't have any kind of speed. Relative velocity exists in Galilean Space-time, and a (relativized) version of it survives into Minkowski Space-time. One might be tempted to argue that light may yet have a speed, just a *relative* one. This would let us avoid the conclusion of my argument, but as an actual proposal it's a non-starter. Whatever the speed of light is, it's not a relative speed.

For a pair of non-light objects, there will be agreement about whether they are approaching each other or receding from each other, and there will be agreement (from each body's point of view) at what rate they're receding from or approaching each other. Even if you consider rotations of the co-ordinate system that don't assign "rest" to one of the two objects being compared (e.g. a reference frame in which both objects are moving) there is a straightforward transformation that will determine their speeds relative to this new comparison object in terms of their relative speeds in the previous frame.

For instance: If one frame represents x as at absolute rest and y as moving to the right, away from x, at $0.2c$, then the frame that represents y as moving $0.9c$ to the right will represent x as moving in the same direction as y at about $0.85c$. These are equivalent representations of the same underlying physical state, but the rate at which x and y move apart goes from $0.2c$ to $0.05c$! If we pick frames that represent y as going faster and faster, we can get the rate of recession as close to zero as we like, but it will never equal zero nor "go negative" (where a negative rate of recession is just a rate of approach). On the flip side, the rate of recession will never go very much above $0.2c$.[2] However, we can use the fact that relative velocity is symmetric in Minkowski Space-time to get a simple form of agreement: In y's rest frame, y will be at absolute rest and x will be moving at $0.2c$ to the left. So, from both x and y's "points of view", the other is receding from it at a rate of $0.2c$.

In contrast, there are no such systematic relationships between a non-light object and a light ray. Changes in co-ordinates change *only* the velocity assigned to the massive/non-light things. Suppose that x also emits a light ray in the same direction as y. Every frame will represent that light rate as having the same velocity in the same direction ($1c$ to the right). It doesn't matter if it's a frame that represents x at rest, or

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[2] How much? Well, the frame that represents x and y as moving at equal velocities in opposite directions will end up assigning them the absolute speeds of $0.101c$. So this frame represents them as receding from one another at a rate of $0.202c$, and that's about as high as it'll get.

as moving $0.85c$ to the right, or as moving $0.999c$ to the *left*. In all frames, the light ray is moving to the right at $299,792$km/s (i.e. $1c$). The only times that the light ray's rate of recession from x is equal to the speed of light is when x is represented as being at absolute rest, but that's only because *every frame* represents the light ray as having *the same absolute speed*![3]

Light is, if anything, one of the few things which we say "move" for which there's nothing interesting to be said about its velocity *relative to* anything else! No other trajectory exhibits such insensitivity across representations to the state of motion of other objects. For non-light objects, their relative speeds can vary but exhibit a systematic relationship which depends on the state of motion of both objects. We get nothing like that from light. Whatever kind of thing the speed of light is, it does not act anything like relative speed.

Could you argue that the speed of light is special, and that it is a relative speed but behaves differently from all other relative speeds? Well, sure. But then why bother calling it "relative"? It isn't relative to the state of motion of anything else. It's the same in every frame! Relative speed may be a no go, but this discussion should inspire us to revisit the question of *absolute* speed. Here's why: This strange feature of light, that it is assigned the same speed in every reference frame, forms the basis of the best argument *in favor* of there being an (absolute) speed of light in Special Relativity. We turn to this argument now.

3 The Argument from Co-ordinate Invariance

The strongest argument in favor of there being a speed of light accepts the arguments from the previous section for everything *except* light. This might sound bizarre (how could light be the only thing in the world with an absolute speed?) but this is the most common response I've received when I make these arguments. The reason that this response is so popular is that it stems from an understanding of co-ordinate systems and how they relate to physical ontology which is very widespread. Here's the argument:

Premise 1: The speed of light is $299,792$km/s in every inertial reference frame in STR

Premise 2: If the speed of light is $299,792$km/s in every inertial reference frame in STR, then light really does have a speed in STR.

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[3] What's more, light trajectories are unchanged by co-ordinate rotations, and cannot be represented as "rest" trajectories. So there is no room to appeal to the symmetry of relative speed, since that kind of agreement required there to be both a frame where x is at rest and one where y is at rest.

Conclusion: Strictly speaking, light has a speed (in STR).

To understand this argument, we must first understand how co-ordinates work. Turning back to Galilean space-time, a co-ordinate system is an assignment of ordered quadruples, $< x, y, z, t >$, of real numbers to each point in the space. The requirements being that simultaneous points are assigned the same t value, and that simultaneous points be assigned x y and z values such that the distances between points be well-represented by the Cartesian distance metric in three dimensions (i.e. $\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$). But what's most important is that these ordered quadruples of numbers be assigned such that *one* of the (infinitely many) sets of parallel inertial trajectories gets privileged, where every trajectory in this set consists of points all assigned the *same* values for x, y, and z (differing only in t value). There is no absolute rest in Galilean Space-time. However, these trajectories are, from the point of view of the co-ordinate system, a kind of "rest" trajectory: an object following one of these trajectories is always in the same "place" (where "place" in the co-ordinate system is just determined by x, y, z co-ordinate). This is why these co-ordinate systems are sometimes called "rest frames" or "reference frames". They add additional structure, in particular absolute rest structure, that doesn't exist in the underlying physical space so as to make that space easier to describe and make predictions about.

The choice to mark that one set of inertial trajectories as "rest" trajectories, in that frame, was arbitrary. If we choose a different set of parallel inertial trajectories to label "rest" (or "xyz-preserving" if you want to be pedantic) trajectories, then that co-ordinate system will be a *different* rest frame. The same way that rotating the axes on a Cartesian plan around the origin will give you different (but equivalent) co-ordinatization of the same underlying space.

The idea is that, even though these co-ordinatizations *seem* to disagree, e.g. one labels the trajectory p as "at rest" in the frame while the other represents p as being in uniform motion, they only disagree about the extra structure they add as co-ordinate systems, never about the underlying physics (e.g. they all agree about which Galilean trajectories are inertial vs. accelerated). So if we take all the reference frames produced by rotating[4] or translating our axes (or by changing our units, etc) and look at what they all *agree* on, we'll know what it means for something to be "true in every reference frame in Galilean Space-time".

For Minkowski Space-time, we can do something similar, but there are two big differences. The first is that its co-ordinate systems bring back not just absolute rest but

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[4] Both in space, by rotating the x, y, z axes on each time-slice, and "in time", so to speak, by changing which set of parallel trajectories get the label "at rest".

also absolute *simultaneity*. When we assign an $<x, y, z, t>$ co-ordinate to every point in Minkowski Space-time, we must pick a set of slices—a "foliation"—among the space-like separated points and assign the same t value to every point on the same slice. This is analogous to picking an arbitrary set of parallel inertial trajectories to label "rest" trajectories. The second big difference is that these two arbitrary choices are not independent in Minkowski Space-time. By specifying a preferred foliation into "simultaneity slices" (or "slices of equal t-value" if you're pendantic) one will end up also privileging one set of parallel inertial trajectories as "x, y, z-preserving" or "at rest" in the frame. The same is true the other way around, by privileging one class of trajectories as "at rest", the resulting co-ordinate system also will privilege one foliation. This is why the "rest frame" locution is still applicable in Minkowski Space-time. Still, while these different frames disagree about much, they agree about the underlying physics.

3.1 Co-ordinate Abstraction Principle

So now we can understand this argument properly. Premise 1 asserts that "the speed of light is 299,792km/s" is true in all reference frames of STR. Premise 2 employs a version of a co-ordinate abstraction principle, or CAP. Here's an example of a co-ordinate abstraction principle for STR:

CAP$_{\text{STR}}$ If 'X' is evaluated as true in all inertial reference frames of STR, then 'X' correctly characterizes part of the underlying physical state.

We could break Premise 2, above, into an instance of CAP$_{\text{STR}}$ combined with a generalization step, as follows:

Premise 2a: If 'the speed of light is 299,792km/s' is evaluated as true in all inertial reference frames of STR, then 'the speed of light is 299,792km/s' correctly characterizes part of the underlying physical state. (Instance of CAP$_{\text{STR}}$)

Premise 2b: If 'the speed of light is 299,792km/s' correctly characterizes part of the underlying physical state of STR, then light really does have a speed in STR.

The conclusion follows from 1, 2a, and 2b.

I will argue that the problem with this argument is with CAP. Co-ordinate Abstraction Principles are far from analytic: just because all the reference frames agree about the underlying physical facts doesn't mean that's *all* they agree about! The only principle that *analytically* follows from the nature of equivalent co-ordinate systems is the inverse of CAP: if inertial reference frames *don't* agree about 'X', then 'X' does not correctly characterize part of the underlying physical state.[5]

Co-ordinate abstraction principles are widely accepted, though usually not in this exact form. Hermann Weyl explicitly accepts one about STR in his *Symmetry* Weyl (1952, p. 132) "What Einstein did was this: without bias he collected all the physical evidence we have about the real structure of the four-dimensional space-time continuum and thus derived its true group of automorphisms.... [I]t is the inherent symmetry of the four-dimensional continuum of space and time that relativity deals with. We found that *objectivity means invariance with respect to the group of automorphisms.* [my emphasis]". Debs and Redhead (2007) call the view that invariance is both a necessary and sufficient condition for objectivity, "invariantism".[6] and reject it in favor of a more nuanced view they call "perspectival invariantism". However, they don't reject the core claim in its entirety; they only object to the *necessity* claim! Even their final position agrees that co-ordinate invariance is sufficient for objectivity. This amounts to the acceptance of CAP.

Despite being widely accepted, there are some serious problems with co-ordinate abstraction principles. I won't weigh in on whether these principles are *always* false, but the case against CAP *as used in this argument* is airtight. CAP faces certain fatal counterexamples. Moreover, no variant of CAP that can avoid these counterexamples will be strong enough to imply Premise 2.

3.2 Against CAPs

I've said that the best argument for there being a speed of light in Special Relativity relies on a co-ordinate abstraction principle, or CAP. I will demonstrate that this principle is false, in its current formulation, by showing that it has clear counterexamples. Then, I will argue that no weakening of CAP_{STR} that avoids these counterexamples will be strong enough to save the argument in favor of there being a speed of light.

According to CAPs, if all the co-ordinate systems, produced by all the acceptable permutations that preserve accuracy about the underlying physics (e.g. rotations, trans-

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[5] That is, Inverse CAP plausibly follows from the meaning of "equivalent reference frame". If these frames are equivalent representations of the same thing, then anything they disagree about must not be a part of the thing they represent.

[6] There are two other tenets of invariantism according to Debs and Redhead, neither of which need concern us here. In addition to the sufficiency and necessity claim, there's also "a connection between the proposed condition for objectivity and the heuristic success [of symmetries in scientific practice]" as well as "a connection between the condition for objectivity and universality" (both p. 63), where a *universal* theory of the physical world has no symmetries in it(s representations) except for "the correct symmetries of nature" (p.70).

lations, and/or changes of unit) agree on 'X', then 'X' is either true or (if 'X' is expressed in terminology that doesn't fit the underlying ontology) it directly describes a real feature of the underlying space.

Is it enough that all the equivalent co-ordinate representations agree about something to make it physically real (or even "physically objective")? Here's a compelling reason to think the answer is "No": Consider a very simple case, the Euclidean plane as represented with 2-D Cartesian co-ordinates. Here's something that all such co-ordinatizations of the plane with agree on:

(3) There exists exactly one point that is the plane's origin, $(0,0)$.

It's important to note: they will *not* all agree about *which* point is the origin, but they will agree about the existential claim. CAP implies (3) because all the co-ordinatizations of the Euclidean 2-space agree about it. (3) is false—the Euclidean plane has no preferred point—and so CAP is false. (3) is a kind of "empty" existential: an existential claim that all the co-ordinates agree on, but they all disagree about which particular is the witness of that existential. So if we keep what they agree on and take out what they disagree about, we're left with an existential without a witness.

We can do the same for physical spaces like Galilean Space-time. The defining feature of Galilean Space-time is that there are no absolute velocities. However, the co-ordinatizations of Galilean Space-time bring in extra structure. In particular, we can use the x,y,z values of points at different times to define the "distance traveled" for a given body. Once we have that, we can define a body's absolute velocity *in that frame*.

Assigning (x,y,z,t) co-ordinates to every point will allow us to define a co-ordinate-based version of absolute velocity. Two non-simultaneous points that are assigned the same x, y, and z co-ordinates are "the same spatial point at different times" Then we can define the co-ordinate-based spatial distance between any two non-simultaneous points. From there, we can define absolute speed in terms of co-ordinate-based spatial distance and global time elapsed.

Every reference frame in Galilean Space-time will agree that, for the inertial trajectory running from $p = (x,y,z,t_1)$ to $q = (x',y',z',t_2)$, there exists a purely spatial distance between the p and q (equal to the distance between (x,y,z,t_1) and q), and that there exists an absolute amount of time elapsed between p and q.

From the distance traveled and the time elapsed, we can define an absolute velocity for that interval. So all co-ordinatizations will agree that "There exists some absolute velocity" for that interval from p to q. A CAP for Galilean Space-time will, therefore, count claims like "Every particle has an absolute velocity" as true (or at least as correctly characterizing the underlying physical facts).

However, the co-ordinates will *not* all agree about *what* these co-ordinates are. They will disagree wildly about the spatial distance between p and q (it could be zero, it could be arbitrarily far). Because absolute time elapsed is part of the underlying physical structure of Galilean Space-time, they will NOT disagree about the time elapsed between p and q. Just as before, we have an existential claim that all the reference frames agree on: "There exists some $\vec{v}$ that is x's absolute velocity" even though none of them agree about how much distance x traveled, and, hence, what x's absolute velocity is!

Now, one might object that CAP, as I've presented it, is cartoonishly strong and that those counterexamples are simply too silly to count against anything other than my ability to formulate philosophical principles. Certainly CAP shouldn't apply to empty existentials asserting the existence of origin points or absolute velocities when there are none! I concede that there *may* be a natural weakening of CAP_{STR} that retains its theoretical appeal without admitting of such counterexamples, but that is outside the scope of this paper. Why? Because *any formulation that rules out this kind of empty existential existential will also rule out light having a speed in STR!* That is, the speed of light is also a kind of empty existential, and so any revision that removes them will bring the speed of light with it.

3.3 The Speed of Light as Empty Existential

Adding co-ordinates to Minkowski Space-time, as described above, introduces "absolute simultaneity" (i.e. foliations of equal-t-value), and "absolute rest" (i.e. a set of xyz-preserving trajectories). From them, we can define up a global sense of "time elapsed" between any two points (just take the difference in their t-values), and "distance traveled" in the same way we did in Galilean Space-time (using the distance metric on the x, y, z co-ordinates of points). And, so, we'll see that in the case of STR, the reference frames are saying: "Light travels *this* absolute spatial distance (subregion of simultaneity slices) in *this* amount of absolute time (distance between slices)... and the ratio between these distances is 299,792 kilometers/1 second".

Consider a scenario where a light ray is emitted at p and then travels through vacuum before being absorbed at q. Compare two equivalent co-ordinatizations of these events, which we'll call the red frame and the blue frame. According to the red frame, the point p is assigned the co-ordinate $(0, y, z, 0)$, and the light emitted at p is absorbed at $q = (2.9x10^8, y, z, 1)$, and so the red frame says that the light ray traveled $2.9x10^8$ meters in exactly 1 second. The blue frame, while agreeing on the starting point being $(0, y, z, 1)$ assigns the co-ordinate $(2.5x10^8, y, z, 0.834)$ to the event of the light ray's absorption. So the Blue frame says that the light ray took just over 8 tenths of a second to make the journey, but went a measly $250,000$km.

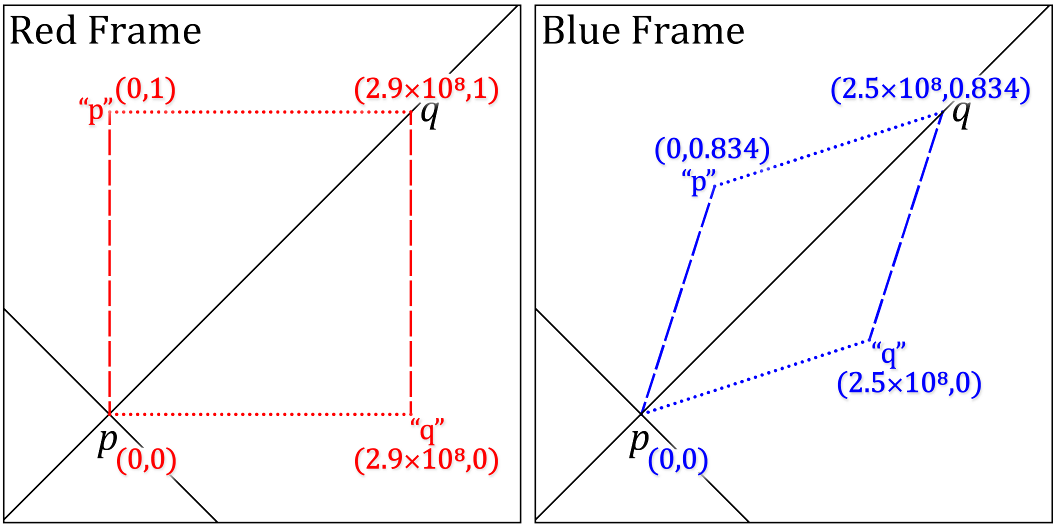

Figure 3: Two frames representing a light ray emitted at p and absorbed at q. Dashed lines represent "rest trajectories", and dotted lines represent "spatial distances" in each frame. The co-ordinates assigned by the Red and Blue frames (y and z co-ords suppressed) only agree that p is located at (0,0).

What's important is that if we look at what parts of space each frame appeals to when it says "this light ray went $290,000,000$m/s" we'll see they are very different. But in the case of STR, the reference frames are saying "Light travels this absolute spatial distance (chunks of space) in this amount of absolute time (distance between slices)... and the ratio between these distances is 299,792,000 meters/1 second". In other words, both reference frames agree that:

$$\text{(4)} \qquad \exists x \exists y \Big(\begin{aligned}[t] & x \text{ is the distance traveled from } p \text{ to } q \\ & \wedge\ y \text{ is the global time elapsed between } p \text{ and } q \\ & \wedge\ \frac{x}{y} = c \Big) \end{aligned}$$

But they will disagree about which parts of space are the distance traveled and the time elapsed. They identify different parts of the space-time as pairs of simultaneous points, and as the "same" spatial point at different times. And they all *deny* that the things the other reference frames are talking about are actually spatial distances or are the actual temporal distances between those particular events.

The red reference frame and the blue reference frame each imbue the underlying space-time with enough structure to define an absolute speed in terms of distance traveled and time elapsed. Both reference frames agree that the same ratio relationship holds between the distance traveled and time elapsed. In other words, both reference frames agree on (4), but they will disagree about *which* parts of space correspond to the distance traveled and the time elapsed. They identify different parts of the space-time as pairs of simultaneous points, and as the "same" spatial point at different times.

As we saw, above, the best argument in favor of light having a speed in the Special Theory of Relativity relies on a premise which was an instance of a Co-ordinate Abstraction Principle for that theory, CAP_{STR}:

Premise 2a: If 'the speed of light is 299,792km/s' is evaluated as true in all inertial reference frames of STR, then 'the speed of light is 299,792km/s' correctly characterizes part of the underlying physical state. (Instance of CAP_{STR})

I have argued that Co-ordinate Abstraction Principles, like CAP_{STR}, face fatal counterexamples coming from "empty" existentially quantified claims—like "there exists an origin point" in 2D Euclidean space or "There exists some $\vec{v}$ that is x's absolute velocity" in Galilean space-time. The only remaining hope for this argument was to replace CAP_{STR} with something which avoids those counterexamples.

In this subsection, I have argued that there is no hope to replace CAP_{STR} with a principle which can rule out empty existential claims and still save the overall argument in favor of the speed of light. This is because "there is a speed that light rays travel in a vacuum and it's 299,792km/s" depends on the exact same kind of empty existentials as the counterexamples I discussed earlier. The special theory of relativity denies that there is any fact of the matter of what the spatial distance is between two space-time points a and b, and it denies that there is any fact of the matter of how much time has elapsed between a and b. But to say that a light ray emitted at p and absorbed at q would have a velocity of c is to accept (4).

Recall, this is not an article about how the speed of light does not exist, it is to resolve the puzzle of how both sentence (1), that Michelson measured the speed of light, and sentence (2), that, strictly speaking, there is no speed of light, could be true.

Now that we have accepted (2), we will feel the full force of that tension.

4 Resolving the Puzzle

So now that we have a puzzle, how do we resolve it? What could it be, that is, that Michelson was measuring? Certainly it's not the speed at which anything travels. However, we cannot discard the speed of light with the same ease we did other products of empty existentials, like absolute velocity and absolute simultaneity. There's a specific number in the speed of light, $299,792$km/s, which cries out for explanation. What could that number signify, and how could it be that Michelson's measurement allowed him to tap into it?

There's no such puzzle about the existence of an origin in Euclidean space-time or of absolute velocities in Galilean space-time, because there's no way that someone could measure anything about those things because they don't exist! And, yet, the speed of light (I've argued) also dies not exist, but Michelson measured it. And it's value isn't one we decided on by mere stipulation or convention. The number $299,792$km/s has do with *something* genuinely real about the world – after all, Michelson was only *approximately right* when he measured it! But what was he approximately right *about*?

The answer comes from our choices of units! What do the meter and the second have to do with the speed of light? Our choices to make these particular lengths or temporal durations our spatial and temporal units were arbitrary ones. However, these choices were also made well before we had any conception of Special or General Relativity, or of the special relationship that light has to the structure of space-time. This is important.

Temporal duration is not a redundant quantity in the Special Theory of Relativity, because while *global time difference* requires absolute simultaneity, there is temporal structure in the Invariant Space-time Interval, which is the fundamental spatiotemporal quantity of Minkowski space-time. Trajectories of non-light bodies have an Invariant Interval length which is best measured with temporal units. According to Minkowski space-time, clocks measure the "length" of their trajectory in terms of the Invariant Interval, and so we can measure interval-length (at least for space-time paths *within* light-cones) using seconds, minutes, and years.

In contrast, spatial length is genuinely redundant in the special theory of relativity. That is, there is no fundamental space-time structure that corresponds to spatial distance (since it requires absolute simultaneity). However, there are derivative, frame-dependent, quantities which can play the role of spatial distance in our experience of the world. There's a natural way to define up one such quantity. This derived quantity is frame-dependent, and its structure is determined by (among other things) temporal structure in space-time.

Consider an inertially-moving particle's "rest frame", i.e. the frame that represents that particle as being at rest. This frame will uniquely determine a foliation (set of simultaneity slices). We can define a derivative "distance" quantity, where that quantity measures the lengths of paths on these slices, using the light-cone structure of Minkowski space-time. Here's the idea, "project" the light-cone from various points on that particle's worldline onto the slice in question.

Call the particle "*x*". Consider the light-cones of various points along *x*'s worldline. If you look at where those light-cones intersect the slice in question, you will get circles of various radii. All the circles will be centered on the point where *x*'s worldline intersects that slice, but they will differ in their radii, corresponding to how far into the future/past, along *x*'s worldline, the origin of that light-cone is located. From this we can get the derived unit of distance, with units like 'light-year' 'light-minute' 'light-second' and so on.

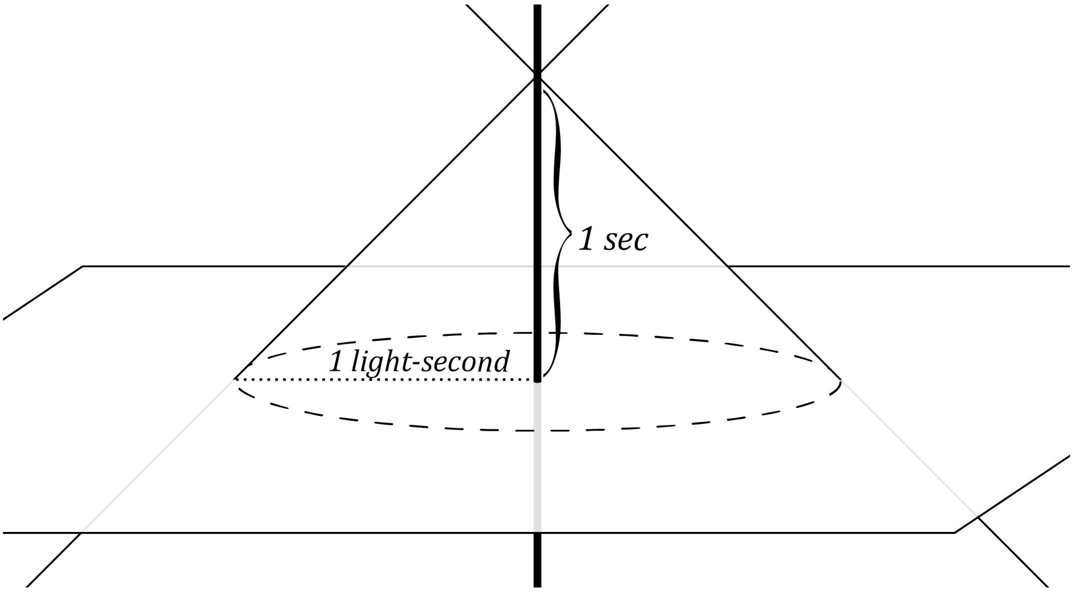

Figure 4: A diagram illustrating the relationship between the second and the light-second.

So our choice distance is, in a certain sense, *redundant*. There's no special role to be played by a unit of spatial distance in STR. Not only are there no distances, but once we've arbitrarily picked a temporal unit (the "second") we already had enough to determine a spatial unit (the "light-second").

But we already picked a primitive spatial unit! We selected the meter via an entirely different method (by defining it as $1/10,000,000$th the quadrant of the great circle around the earth passing through the *Meridien de Paris*). What Michelson measured wasn't a speed, but rather something about the relationship between our arbitrarily chosen unit of distance and our arbitrarily chosen unit of time. While this is a relationship between two conventional choices, their relationship is one that we cannot determine by reflecting on our convention alone. It requires us to examine the world. This relationship holds because Special Relativity allows us to take a unit of time and use it to define a unit of distance.

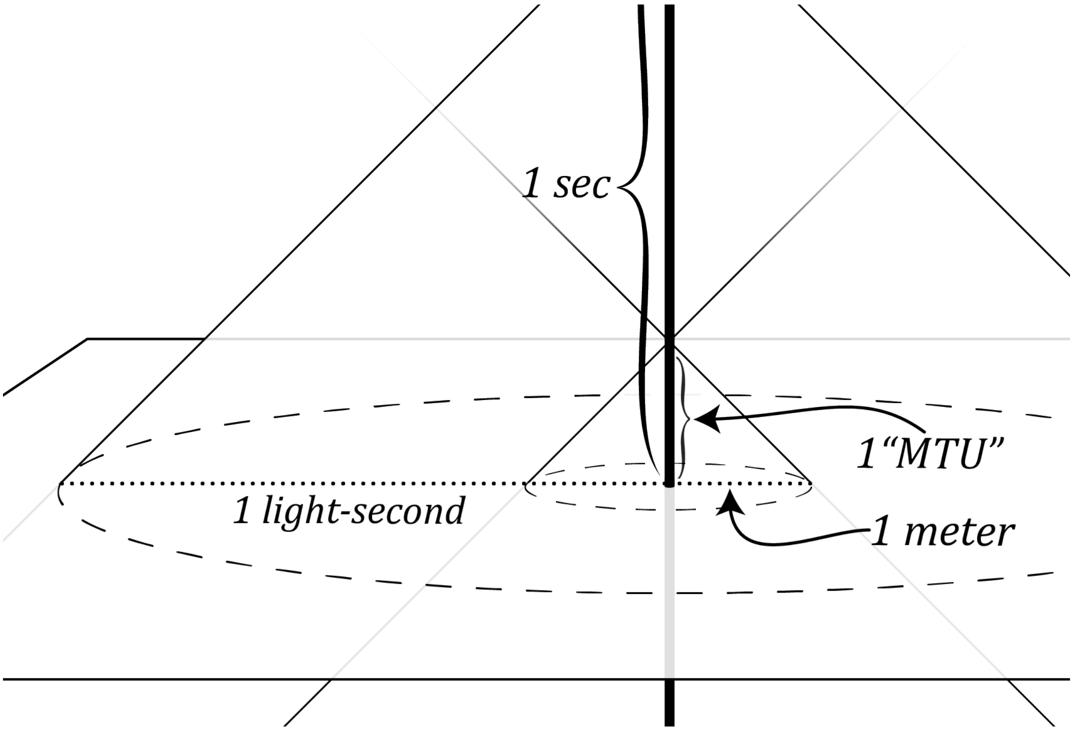

Figure 5: The speed of light can be understood as the *spatial* ratio between 1 light-second and 1 meter, or the *temporal* ratio between 1 second and 1 "meter-transit-unit" or "MTU". Where 1 MTU is the temporal interval between the event of x intersecting a given flat hypersurface (specifically one x's rest frame designates as a simultaneity slice), and the point(s) on x worldline whose future(/past) lightcone's intersection with that hypersurface forms a circle of radius 1m around x. Diagram not remotely to scale.

Michelson's attempt to measure the speed of light actually served to measure the relationship between the two spatial units, both selected arbitrarily. The "speed" of light is actually the *spatial ratio* between the meter and the light-second. Alternatively, it is the *temporal ratio* between the invariant interval lengths of 1 second and the time it takes light to traverse one "meter"—call this 1 MTU (for "Meter Transit Unit")[7]—as depicted in Figure 5, both measures of time. The light-second is $299,792,458$ times longer than the meter. The length of the light-second and the length of the meter were fixed by decisions made long ago, but the fact that they were commensurable *at all* wasn't revealed to us until the advent of STR. Even though both the second and the meter are the products of convention, the value of this ratio is an *a posteriori* fact.

5 Conclusion

Even after all of this, one might wonder whether it's really correct to say that, strictly speaking, there's no speed of light in Special Relativity. After all, the ratio we identified in the previous section is a real, mind-independent feature of the world. Perhaps the right thing to say is that we discovered that the speed of light *exists* but it is a different, more metaphysically derivative, entity than we expected. In some sense, this move is always available if we're flexible enough about what we take our terms to refer to. When we discovered that there's no two non-identical entities that are Hesperus and Phosphorous, but that both are just the planet Venus viewed at different times of day, one could make the same move. Yes, both Hesperus and Phosphorus really do exist and really are non-identical, but they are not celestial bodies, but something akin to atmospheric phenomena (the same way that sunsets and sunrises are different things, despite both being the sun). Instead of saying there's no ghost haunting the old McCreary house, we can say we've discovered the ghost haunting the house *does* exist, but that it's more a metaphysically derivative entity than we expected: specifically, a character in a shared fiction authored by the house's inhabitants.

5.1 How Not to Save the Speed of Light

I think we should resist such a response (as if the examples I chose to illustrate the move didn't make that obvious). Some of the concepts that we encounter in our physics and metaphysics are arrived at by causal or explanatory ostension—we say, e.g., that

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[7] Or, if you prefer, "Reverse Light-Meter", "Light-reteM", or "the unit of time t such that 1 meter = 1 light-t". You might also refer to it using the somewhat jocular "jiffy": 1 MTU is equal to either one hundred or *one quadrillion* jiffies ('jiffy' has been used to denote both the time it takes light to traverse 1 centimeter, according to Gilbert Lewis (1926, p.76), and the time it takes light to traverse 1 femtometer,one "fermi", according to Harrison (1981) following a suggestion from Richard Tolman).

‘water’ refers to whatever it is that’s filling the oceans and lakes and falling from the sky, or that ‘spin’ refers to whatever it is that explains why electrons are deflected by certain magnetic fields in ways that resemble the behavior of classical rotating charged particles. However, not all of our terms function this way. Often we construct singular terms in a way that combines theoretical terms whose meaning we already understand, when we say “the half-life of Plutonium-238” or “the center of mass of the Milky Way galaxy”, we expect that these terms will pick out a period of time, or a point in space in-and-around the Milky Way galaxy. There’s less flexibility for terms like these, because we already know what half-lives and centers of mass are. In our case, we already know what speeds are, both the core concept of a speed as distance traveled over time elapsed, and the more nuanced notions of relative/absolute speed as the magnitude of relative/absolute velocity. This means that composite terms like ‘the speed of light’ do not admit of much theoretical stretching or referent magnetizing. As such, we don’t have the flexibility to say “there are no speeds in Special Relativity, but, *strictly speaking*, there *is* a speed of light in Special Relativity”. (As a reminder: we (of course) don’t need to be so stingy with existence if we *aren’t speaking strictly*. But the purpose of the response we are examining here is to resist sentence (2): “Strictly speaking, there is no speed of light in Special relativity”)

One can make a more plausible version of this same response by arguing that the speed of light is what Robertson and Wilson (Forthcoming) call a “theoretical relict”. A theoretical relict is a “theoretical entity posited by a superseded yet once-successful scientific theory”, where the newer scientific theory that replaced the old does not posit this theoretical entity. Wilson and Robertson propose that we can treat some theoretical relicts as existent but metaphysically higher-level entities. They avoid the problem I raised in the previous paragraph (in the form of a worry due to Saatsi (2022)) by arguing that, for the theoretical relicts which exist as higher-level entities, any theoretical terms which apply to both the higher and lower metaphysical levels are ambiguous in their meaning. Whether a given use of the phrase “time elapsed”, e.g., refers to the global passing of Newtonian Absolute Time, or to the Invariant Relativistic Interval length of a single object’s trajectory through Space-time, will depend on the context and, in particular, on “our descriptive and explanatory goals” (Robertson and Wilson, Forthcoming).

I can see how the project of Wilson and Robertson might be used to save entities like Newtonian Space and Time. They are the theoretical posits of a successful physical theory which was superseded by modern space-time theories. For Wilson and Robertson, Newtonian mechanics is a metaphysically derivative approximate theory that applies to a diminished physical domain (low-relative-velocity motions), to make higher-level descriptions and explanations. Its theoretical relicts, like Absolute Space and Time, are metaphysically derivative entities that are appealed to as part of those descriptions and explanations. However, I cannot see how this kind of move will save the speed of light in particular. It is not a holdover from an older, explanatorily successful, theory that happens to closely approximate Special Relativity.[8] It's alleged to be a theoretical posit of Special Relativity *itself*, but we have seen that this is not the case. And, if the speed of light isn't really a theoretical entity posited to exist by Special Relativity, then it won't matter whether or not the theoretical posits of Special Relativity survive as theoretical relicts once it is superseded by General Relativity or some theory of Quantum Gravity. So, while Wilson and Robertson's account does avoid my initial worry, it doesn't look like it will apply to the case of the speed of light in Special Relativity.

5.2 Where does this leave us?

We have now resolved the tension from the beginning of the paper. There is no speed of light in Special Relativity because there are no speeds in Special Relativity, and the fact that a light ray in a vacuum will be assigned a speed of $299,792$km/s in every frame does not contradict that. Yet it is also true that A. A. Michelson measured something mind-independent about the physical world when his experimental setup yielded a "speed of light" of $299,944$km/s(±51). Indeed, given that he was already using the terms 'kilometer' and 'second', it is the very structure of Minkowski Space-time that guarantees there was something was there for him to measure. He did not measure a speed, but his experimental result reflects the fact that distinct spatial and temporal scales are not necessary in Minkowski Space-time. Temporal units, like the second, are useful to capture the purely temporal structure of time-like trajectories. But there is no purely spatial structure in the underlying physics, and any line which one frame depicts as "purely spatial" another frame will depict as a trajectory.

But Minkowski Space-time does explain how one can use temporal scales to derive a spatial scale *within a given rest frame*. I describe this process in Section 4, and show how we derive the "light-second" and "light-year" by projecting lightcones onto those surfaces which that frame treats as "simultaneity slices". This process, so described,

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[8] Why can't we use the fact that the existence of absolute velocity is a consequence of the existence of absolute space and time, and so survives as a higher-level theoretical relict of Newtonian mechanics? The problem is that Newtonian mechanics survives as a higher-level theory that applies within a restricted domain, and the kinds of scenarios that Newtonian mechanics approximates well and gives good explanations for are ones where the relative velocities are low.

can be run in reverse, first with a co-ordinate dependent “spatial” circle of some radius and “projecting” along a lightcone to yield an interval of time. From this process, we take a circle with radius of 1 meter and project back to arrive at the temporal interval I dubbed 1 Meter Transit Unit, or “1 MTU” (alternatively, 1 unit of Meter Transit Time). The second and the MTU are both temporal intervals, and so stand in some ratio relationship, independent of any co-ordinatization: 1 second = $299,792,000$ MTUs. This feature of the underlying physical world is what it is in virtue of which we can say that Michelson’s measurement was a close approximation of the truth.[9]

One moral we might draw from the second half of this paper is that the arbitrary representational choices (e.g. picking a unit) we make in science can constrain our future investigations in ways that can’t be easily “kicked away” as we move to newer theories. In some ways, this is a component of the over-arching moral of this story: We should not let ourselves be misled by our own mathematical representations. The artifacts of our representation do not wear their artifactuality on their sleeves. Even if a whole family of equivalent co-ordinate representations agree about something, that doesn’t mean it’s not also an artifact of the representation. Insofar as this is a distinction which makes physical sense, it is evidence against invariantism in the philosophy of science. Even if we are not committed to realism about the underlying physics, the clear failure of co-ordinate abstraction principles to distinguish between physical facts and obvious representational artifacts should give anyone pause.

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[9] Is it really right to say that Michelson measured this relationship between the second and the MTU? He did not conceive of himself as doing that, and the physical theory required for him to even make sense of such a proposal would not be developed for some decades. I am very permissive about what counts as measurement, and I think that a close relative of reference magnetism applies to measurements in science. Michelson set out to measure a feature of light rays and how they move through space, and we should interpret that charitably and treat him as having measured what his apparatus, in fact, indicates about how light moves through space. What is that? Michelson constructed an experimental setup which correlates the spatial structure of the path he had the light-ray follow (which he measured in meters, feet, and miles) and the amount of time it took for the light ray to traverse a portion of that path (which he measured in seconds) wherein it makes a round-trip journey starting from and then returning to the same rotating mirror. From the mirror’s rest frame, it’s clear that such an apparatus would also allow us to identify the value of the Meter Transit unit on the mirror’s world-line. The round-trip journey of the light would take some time t, and the length of that path was 605.4m, so $t = 1210.8$ MTU. The time between the light ray’s departure and return would be approximately 4038 nanoseconds. Divided by 1210.8, and that gives us 3.335 nanoseconds = 1 MTU.

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