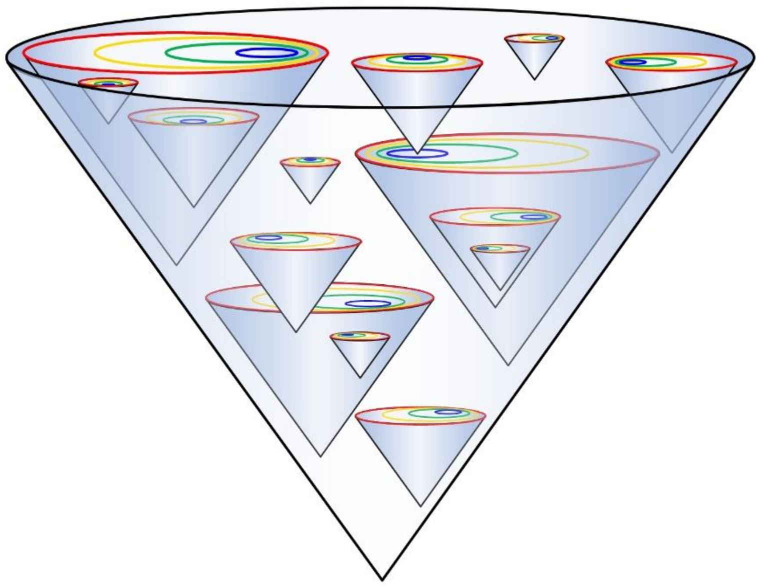
Smooth Spacetime is Only a First Approximation
(Edited Transcript)

Terry Bollinger
2025-03-15.13:00 EST Sat



The full symmetries of Special Relativity only apply within isolated accelerated systems of matter

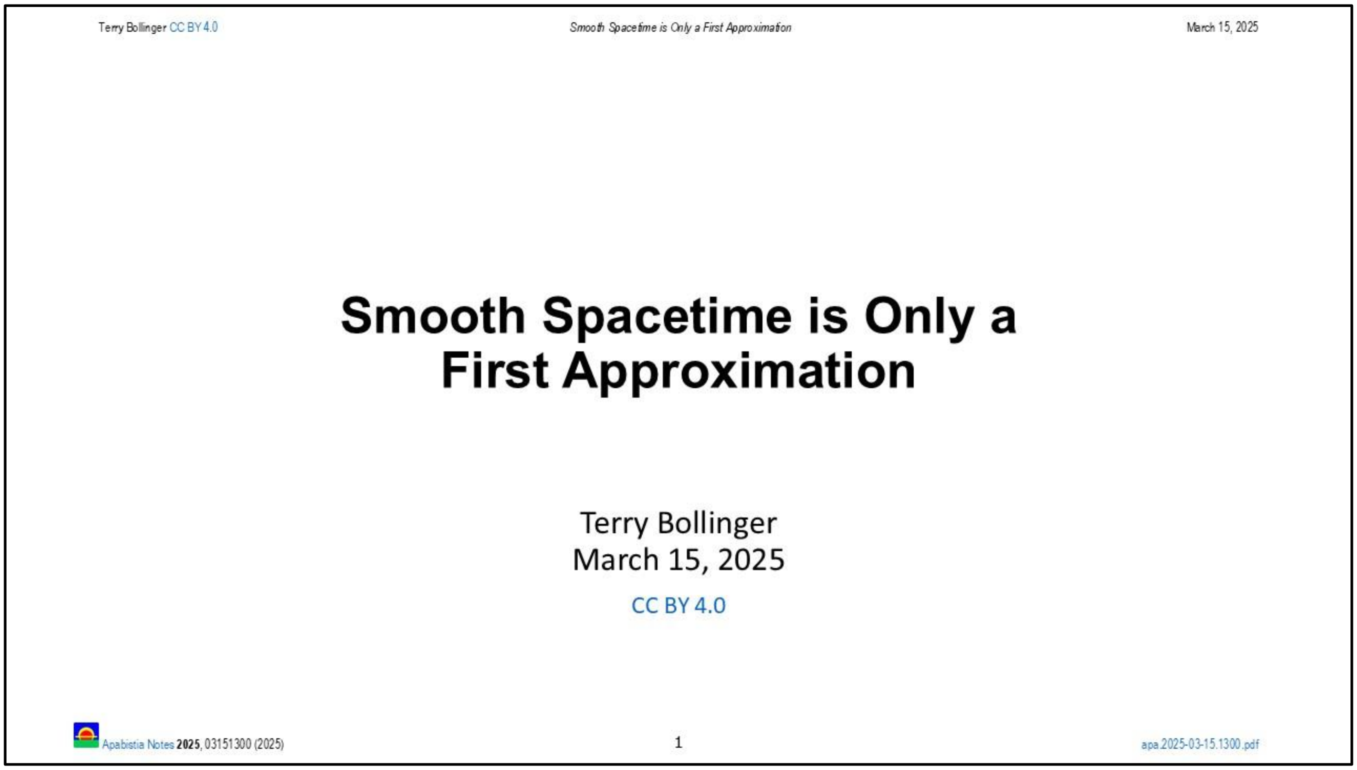
This is the edited YouTube transcript with references. You can view the full video at https://youtu.be/HLH6td0jeAo

Relevant discussion before the presentation:

[0:00] Terry Bollinger (TB): …I just have so much fun [with this topic]. There's a certain point at which you start to recognize the simple experimental fact that the only time you can talk about time and length is when you have matter, and you stop trying to make everything into a nebulous form of spacetime that can *never be measured without matter and energy*. It *really* flips things upside down, and opens up a lot of different exploration possibilities with a lot less noise in the math. Suddenly, you're constrained in your math and you have to focus on saying, "Well, what is it actually *doing*?"

Right now, it's very easy just to get lost in huge complexity, as I…talked about in the last talk, that just doesn't *go* anywhere.…We've seen that, gosh, 45 years now? Expanding complexity and very little convergence. It would be nice to have some simpler approaches, and I think this is very definitely [such] a route: [That is, taking] a sparser route and saying, "How is *this* generating all of *that*?"

So, [this is] a fun topic. And once you once you click onto it, it's hard to go back. I look at the way I used to think of physics, and it just looks *so* noisy. It's the same math, in many cases, but it's a different perspective [in which] you say, "Yes, but that's just what you're generating by *poking* it with a gigantic particle accelerator." *Of course* you're going to get a lot of complexity — that's what happens when you blow things up! They *explode*! That doesn't mean that that's the everyday reality of what that system is. It just gives a different perspective where you have a lot less infinities laying around.…



[3:46] Helen Ma (HM): [Welcome] to our third event [with Terry Bollinger.] It's a pleasure to have Terry, [who] is a computer scientist. So, Terry, when you're ready, let's start.

TB:… The topic for today is [that] smooth spacetime is only a first approximation. What I mean by that is we have a standard model in mathematics where we [view] the structure of spacetime as a *smooth* — as in, something that goes to infinity, [has] infinite variety, [and is capable of] infinite detail [within] any particular [local] piece of spacetime.…

I'm suggesting [that] we need [a] different approach,… [one] more attached to the… physics we experience. [My main] point… is… a remarkably simple one [that] goes back to the original 1907 papers by Albert Einstein in which [he gave] a… mechanism… [for translating] between coordinates in different inertial systems.

[Thus I] necessarily [gets into some] math, but none of [it] is complicated. In fact, it's all just algebra —… no tensors or anything like that. That [level of math is] not necessary [for this] debate.…

[3:52] … The purpose [instead] is to look at some details of how we deal with special relativity — [details] that argue that we need to be more attached to physical mechanisms — clocks and rulers — which are what Einstein talked about *entirely* up until 1911. He never talked about Minkowski spacetime until *after* that point. Up until 1911, his *only* focus was on mechanical devices that would actually *record* time, that would actually *express* time, [and] that would express *length*.

That turns out to be important because there are things you can do with — [things]that Einstein showed — that you just *cannot do* with a pure mathematical abstraction because the mathematical abstraction immediately takes you away from those measuring devices. There is some really interesting history there, too, about why Einstein did this complete flip after 1911 from using clocks and rulers — and complaining that he didn't understand what Minkowski was *saying* — to completely embracing Minkowski's spacetime, and it has to do, in part, with the fact that Minkowski, unfortunately, died of appendicitis. Einstein was … grief stricken [and] sad about what had happened. So, [there is] some interesting history there, as well as the actual physics.

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A Small Omission with Broad Implications

The equation for translating time coordinates in special relativity…

$$t' = \gamma\left(t - \frac{v}{c^2}(x)\right)$$

… needs one more parameter, $l = \text{length}$, to work in all situations:

$$t' = \gamma\left(t - \frac{v}{c^2}(x - l)\right)$$

We don't notice because the *point approximation* of pretending moving objects are "mostly" point-like in time works well for most situations.

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[5:13] The first thing — and, actually, the central point of this [presentation] — is that there [is a problem in one of the] equations in Einstein's 1907 paper [that] expands on his 1905 special relativity papers. These equations give you a way to translate between two inertial coordinate systems, [and] these are absolutely standard algebraic equations. You can express them in tensors and other ways, but algebra does quite fine on expressing these. [However,] if you look at them closely, there is a small problem.

[Bringing this problem up] is unavoidable. The two physicists I respect more than anyone are Richard Feynman and Albert Einstein, in terms of their thinking. It is just amazing to read their works and their papers. Nonetheless, you can still have small problems — and sometimes, those small problems can turn into larger ones. The problem, in this case, is that the parameter for translating *time* is *missing* one element, and that element is the *length* of a physical system.

The reason this is important is because [using the length of] a physical system attaches the equation to material objects in a way that [Einstein's original] equation does not. That is turns out *not* to be a trivial difference. And yet, if you don't add this one, simple parameter, you wind up with paradoxes — you wind up with false results. And the results are pretty glaringly false. They're just *wrong*.

[If that's so,] the obvious question is: Why have [Einstein's original equations] worked so well for so long?

The reason is pretty simple. As long as you [can plausibly apply] a *point-like approximation* [to an object moving an observer's much larger rest frame] — [e.g.,] if you have a [small] spaceship traveling through [vast] interstellar space, or if you have a [microscopic] particle going through a [human-scale particle] accelerator — the first [version of the time translation] equation, [Einstein's version,] works fine.

Now, the reason is that [in such point-approximation cases,] you don't have any [sufficiently significant] length [issue] to impact the outcome. You wind up with some odd little problems in how to interpret it sometimes, but the point-approximation works very well. So there's a [good] reason why [Einstein's traditional coordinate translation] equations are very effective for what they do.

[However,] if you look at larger cases — when you have, for instance, two galaxies colliding with each other, [or] if you have particles in a colliding accelerator where the particles are trying to be modeled at the quark[-gluon] plasma level, things change a little bit. There are, [for example], specific differences even on the example of colliding lead nuclei [where] you have to be a little bit careful about this very equation. What happens with that it does make a difference — and presumably a predictable difference — although you'd have to get some very detailed data to do it so that's in many ways that's the theme of this whole talk is saying add one parameter, which is the length of the unit accelerated, notice that includes history now we're talking about not just a complete abstraction but you have to have the history and that leads to a number of interesting consequences.

…

[10:18] The main point is that point-approximation works really well. You don't have a theory that lasts over a century [if it] doesn't work well! And [the original Einstein coordinate translation equations] work very well.

But there is an important qualification…, [and] you see the fraying at the edges when you start talking about very large systems that collide each other or go at very high speeds. The first examples were [the extreme] cosmic jets that they found, I think, in the 70s, 80s, 90s — that started posing some interesting [explanation] problems.…

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1 of 3 Root Problems in Special Relativity

(1) Objects suffer no permanent changes from being set into motion and brought to rest.

Einstein realized the risk in this coordinate transformation assumption when he flagged it in a 1907 footnote:

> *1) This conclusion [that the coordinate transformation equations are symmetric from both frame views] is based on the physical assumption that the length of a ruler and the speed of a clock do not suffer any permanent change as a result of these objects being set in motion and brought to rest again."*
> — A. Einstein, 1907. Page 420, Section 3, Footnote 1), Coordinate-Time Transformation, in [1].

The assumption fails because Lorentz contraction and internal clock resynchronization are *physical* operations applied *only* to the accelerated system. When brought into motion and to rest again, the accelerated system is first squeezed and unsqueezed in historical events requiring time and energy. Meanwhile, the larger rest or parent frame is unchanged. Another irreversible change is that physics-time synchronization after acceleration introduces irreversible "lost time" gaps in the experienced (versus physics) definition of time in the accelerated system.

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[1] A. Einstein, *Coordinate-Time Transformation* [Sec. 3, pp. 418–420, in '*About the Principle of Relativity and the Conclusions Drawn from It*,' pp. 411–462], Jahrbuch der Radioaktivität und Elektronik **4** (4), 418–420 (1907). https://sarxiv.org/ref.1907-04-04.0418.engl.pdf

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[10:57] To address the elephant in the room, I'm saying point-blank [that there are] three problems [in Einstein's 1907 equations]. [They] are all minor, but they are worth pointing out because they *do* make a difference. In some cases, [that difference is] not as minor as you might think.…

I remember when I ran across [the] most interesting problem in [Einstein's] 1907 special relativity expansion. Einstein put in a little footnote [that] says, "The equations derived above" — of which I just gave the example of the time equation — "… assume there is no permanent, irreversible change to the object when it is sped up and slowed down." This is an abstract view of the object. [It's the idea that] acceleration is a purely mathematical process — that is, essentially, what [Einstein] is saying.

It turns out — and I'll get into this in later slides — this is simply *not* a correct assumption. [People can get away with thinking of] Lorentz contraction … as an *abstract* issue when [they apply it only to small systems]. When you apply it to *large* systems — the example I always like to give is satellites in space — [the abstract interpretation of acceleration no longer works.] …You *physically have to move the pieces closer together*. It doesn't just occur by magic — it's not something that is an automatic given.

We don't notice it on Earth because, [for example,] when you get in a car [and accelerate,] any compression is…so trivial compared to the velocity you're going [that] you won't notice it. But when you start working with really *large* systems, the assumption that there is no physical change suffered by the system is…experimentally *not correct*. You have [to use a compression process that] differentiates [between the two systems].

That's important because you're making a distinction between the two systems. …If you have to compress one system but you're *not* compressing the other system, you have created…a historical event that cannot be reversed [and thus] *distinguishes* the smaller [accelerated] system from the larger system in which it's embedded.

If you want a simple explanation for why we get Twins Paradoxes, *that's it right there*. Most … explorations of the Twins Paradox fail to acknowledge that you accelerate and [thus]…irreversibly alter [the] smaller system, the spaceship, [but] do *not* [accelerate] the person back on Earth.

People then get into all sorts of abstract [discussions] such as, "When does the time dilation happen?" I'll *tell* you when it happens: It happens *continuously* the instant you accelerate that system. You can put monitors up to check that all the way — and that's not my own thought experiment. That's Einstein's.

And yet, we tend to skip over the fact that the way [Einstein] came up with the Twins Paradox was to recognize that the time dilation effect is continuous, instantaneous, and a result of the acceleration. [But you also] physically change the system, [which Einstein seemed not to notice]. …That's a little surprising, especially considering Einstein was one who *explored* [the idea.] That's how he *found* the Twins Paradox.

But you *can't* just ignore that feature [of acceleration changing the system]. People get [into] very complicated [explanations such as,] "When you turn around, *that's* when the time dilation occurs!" *None* of that is what's going on here! It's actually *far, far* simpler: [If you] accelerate [a clock], [you] slow it down. You [distinguished] between clocks] at that point. You have also physically contracted — Lorentz contracted — [the clock] at that point.

I'll get into this later, [but obviously, all of this raises the issue of], *"What happened to the [Poincaré] symmetries?"* [The answer is that the] symmetries are *still there* — this is what I love about this! … The Poincaré symmetries *still exist*, but you have to *constrain* [where they apply] in a very careful fashion. That's why, if you look at them … but don't *recognize* the constraints, you [incorrectly think you are] seeing this perfect, [all-encompassing] mathematical symmetry. [That is why] if you *ignore* those constraints, you start getting these *weird* paradoxes. You start thinking, [for example,] "Well, who's *slower* than the *other* in the big picture?"

That's an interesting result of this one small assumption that [Einstein] made.

2 of 3 Root Problems in Special Relativity

(2) Two inertial frames can share the same coordinate origin without creating paradoxes.

To derive his inertial frame coordinate transformation equations, Einstein assumed in 1907 that one can:

1) "… choose as the starting point of time in both systems the moment at which the coordinate starting points [$(t, x, y, z) = (0,0,0,0)$ *and* $(t', x', y', z') = (0,0,0,0)$] *coincide;"*
— A. Einstein, 1907. Page 418, Section 3, Coordinate-Time Transformation in [1].

This assumption fails for a curious reason. Even though Einstein found, identified, and quantified the different definitions of simultaneity across inertial frames — and, in his transformation equations, uncovered the "time slope" algebra needed to quantify these changes — he never applied his time-per-length math to predict times for clocks at the back and front of a moving (e.g., a train) system. Had he done so, he would have found that forcing the origin of a newly accelerated system to coincide with the origin its parent system requires physically resetting clocks to false-past times for which *no events exist*. Separating the parent and child frame origins removes false-past times, but cannot resolve the disparity between experienced time and physics time in accelerated systems.

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[1] A. Einstein, *Coordinate-Time Transformation* [Sec. 3, pp. 418–420, in '*About the Principle of Relativity and the Conclusions Drawn from It*,' pp. 411–462], Jahrbuch der Radioaktivität und Elektronik **4** (4), 418–420 (1907). https://sarxiv.org/ref.1907-04-04.0418.engl.pdf

[15:14] Second problem: "Two inertial frames can share the same coordinate origin without creating paradoxes."

Now, *this* one is *subtle*! This is *not* something you can look at and say, "Oh… *obviously* there's a problem there!" [But] there *is* a problem here — [in part, precisely] because it *is* such an innocuous and reasonable suggestion. Einstein is going through his equations and saying, "Well, *obviously*, we can assume these are homogeneous equations, [so we can have the origins of the two] coordinate systems coincide at the same point." [Thus, following Einstein's lead,] you have x, y, z, and t all equal to zero at the same point in those two systems.

[The problem is that] you *can't do that*. This is what's so funny about it! It's such an *obvious* and *easily assumed* feature of the mathematics that you say, "Well, *surely* I can [also] do that in the physical system."

However, it turns out that this causes problems — and the problems are paradoxes that create things that *don't exist*. So you have to do something a little different. This gets into that issue about why you have to add *one more* parameter if you want to get outside of [relying on] that point-approximation [model].

So again, this is a problem… this was an actual *omission*. In fact, one reason why I think Einstein [later] got frustrated with [his original clock-and-ruler approach and switched to Minkowski space] was that [*after*] he made this assumption, [he never] went back … to question it. It is such a straightforward [assumption]! Why *would* he question it?

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3 of 3 Root Problems in Special Relativity

(3) Declaring forward and backward lightspeeds to be identical causes no paradoxes.

After demolishing two arbitrary assumptions in a 1911 talk, Einstein ironically added one of his own making:

1) *"… since we now know that the lack of a preexisting universal time definition makes it fundamentally impossible to measure any speed, particularly the speed of light, without first applying an arbitrary determination, we are entitled to make just such an arbitrary stipulation regarding how light propagates. We stipulate only this: The speed of light propagation in a vacuum from A to B is the same as from B to A."*
— A. Einstein, 1911. Page 8 of *The Theory of Relativity* [2].

Einstein was keenly aware of the experimental difficulty in defining one-way lightspeeds, and so refused to define the speed of light using anything other than an out-and-back loop. However, since different lightspeeds in the forward and backward direction were part of Lorentz's earlier theory, Einstein used impossibility of such proofs as grounds to *declare* the two speeds equal. Unfortunately, his proof focused on lightspeed observability within a *single* inertial frame and overlooks the complexity of observing effective (causal) lightspeeds in other frames. For example, an oscillator vibrating in the direction of motion demonstrates different definitions of *time* in the forwards and backward directions, which are equivalent to diverse forward and backward lightspeeds.

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[2] A. Einstein, *The Theory of Relativity* [with Figures], Naturforschende Gesellschaft, Zürich, Vierteljahresschrift **56**, 1–14 [Jan.] (1911). https://sarxiv.org/ref.1911-01-16.figs.pdf

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[16:46] Third problem: This one *fascinates* me!

Einstein is notorious in a good way — *famous* — for getting rid of extraneous assumptions: Assumptions that you don't *need*. The assumption that length is the same [for all observers] seems like a very obvious assumption, [so it's] no wonder people thought that. But Einstein said, "Well, that's not necessarily true. Length can change. You can see [length] as [unchanging] inside of your system, but other people may see it differently." He did the same thing with time, [saying] that, "[Assuming time passes identically for all observers] is another extraneous assumption."…

So… [Einstein has a] wonderful little…1911 paper… [which] was…actually a lecture that he gave…

([A quick sidenote:] Someone transcribed [this lecture he gave into] notes, [but whoever did it was rushed and] missed [transcribing] an entire sentence at one point. …You can find a more readable [English translation of the paper at my website,] where I've added figures [to give some idea of] what Einstein…must have been drawing on a blackboard because he…refers [at times] to something [previously written.] So, I've tried to [recreate] figures that capture the essence of [the figures he drew]. I feel sorry for the guy who was transcribing that lecture. He was trying to get all the notes [and figures] down, but he only got one figure!)…

… [Getting back to the content of his lecture, at one point, Einstein] makes this assumption — he just *inserts* it — and says, "Well, you know, Lorentz said the speed of light can vary in opposite directions. That's part of Lorentz's theory." Einstein looked at that [issue very carefully] — and again, I *love* the way Einstein thinks —…and said, "You know, even if [lightspeed] *does* vary in [opposite] directions, *you can't tell*."

[So, for example,] if the speed of light for you sitting in your chair is a *billion times faster* going forward and *a billion* times slower in the opposite direction, [*you can't tell*.] (They have to be [inverse] ratios, by the way; [many presentations and papers] miss that point.) [That is,] there is no way that physics allows you to *detect* that you have an asymmetric speed of light. …

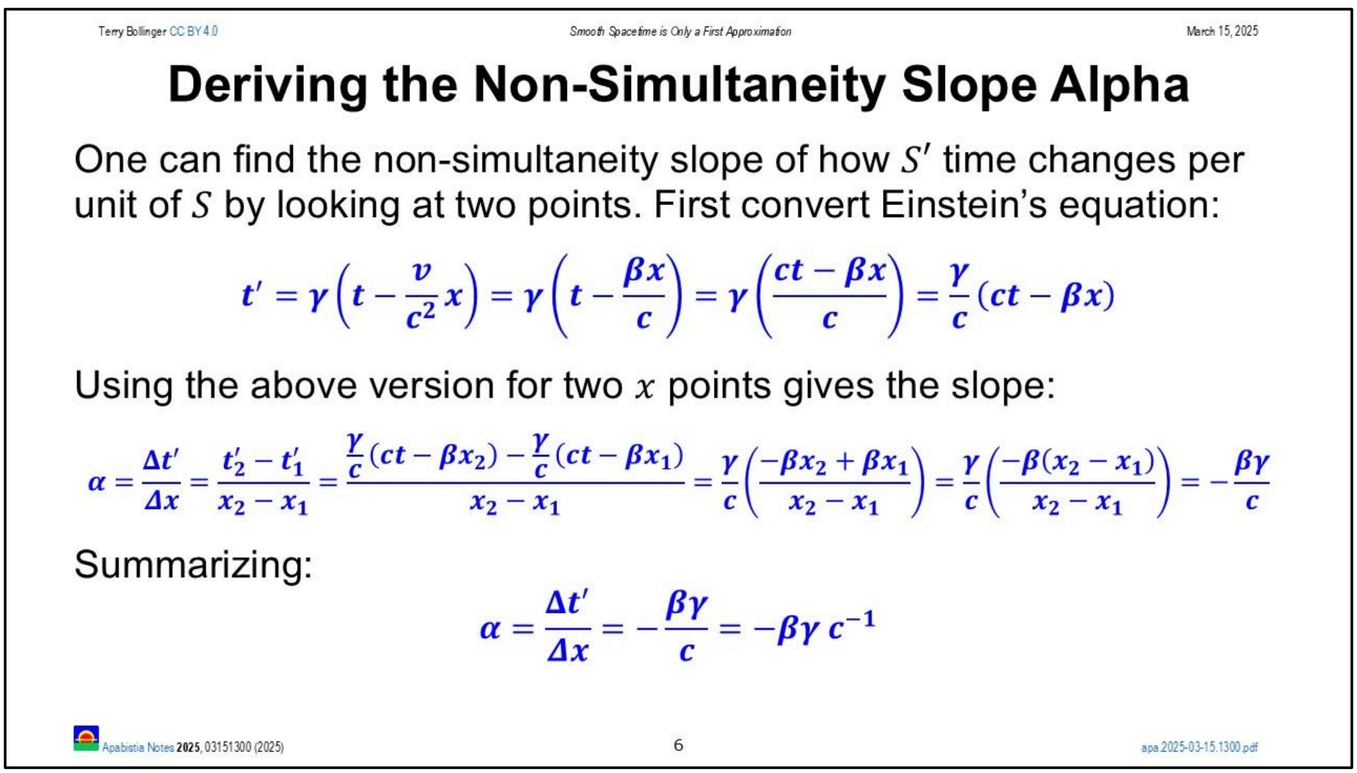
Einstein was very aware of this, [which is why] he always [and only] defined the speed of light in terms of an [out-and-back] loop. … [But more importantly,] he said, “Well, you know… since you can’t *detect* it, I’m just going to *declare* [the forward and backward velocities of light] to be the same. I’m going to add an *arbitrary constraint*.” So he adds a stipulation — which is exactly [the kind of arbitrary constraint] he had just gotten rid of! He got rid of *two* stipulations — and then, [ironically,] he added a *third* stipulation!

The problem with [Einstein’s added] stipulation … is that it messes up relationships *between* frames.

[So, while] it’s absolutely true that you cannot tell *within* one frame that speed light is different in opposite directions, if you [have] two frames [in which an object defining a smaller] frame whizzes by you at high speed, you [can] look at … clocks [in both frames] and you [can] look at the speed of light [in both frames]. You see the *same* speed of light [within your own frame.] But to *you*, time is all *messed up* for the other person. That [person’s] time is very *slow* in the … forward direction and very *fast* in the backward direction. …

If you want to, you can express that [difference in clock speeds by saying] his *effective* speed of light is *enormously* faster in one direction than the other. Or, you can [continue to] express it in terms of time. Either way [works].

When Einstein [added] this stipulation, he inadvertently clobbered the ability to express that [frame-observing-frame disparities in how lightspeed works.] By doing so, he created these paradoxes — strange little problems that you can’t deal with in a very straightforward way. Using Minkowski representation further hides that problem. Minkowski space is great, but it also obscures this very issue because it doesn’t [have any room to] express [two-way time differences well].



[21:01] Einstein talked about non-simultaneity. This is one of the most fascinating results Einstein came up with. He said that *your* definition of things happening at the same time is not the same as *my* definition of things happening at the same time.

The idea of simultaneity has fascinating physicists ever since, because they say, “How can this be? How can people have different definitions of what is simultaneous? Isn’t the world more or organized or orderly than *that*?”

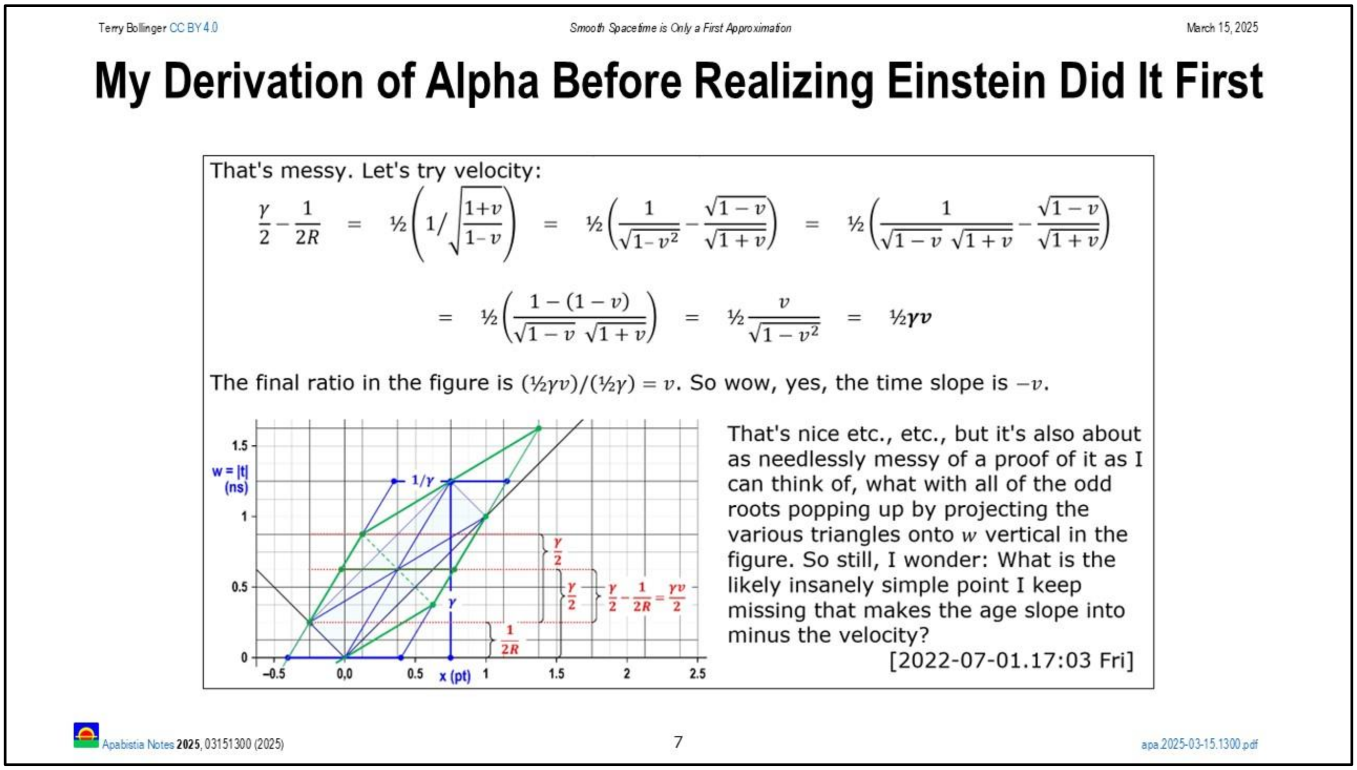
Einstein used this example of a train and lightning strikes. You have two lightning strikes, simultaneous, and he shows that even if they look simultaneous by the *embankment* of the train, they don’t look simultaneous *inside* of the train.

So Einstein was keenly aware of this, and was the one who promoted the idea of non-simultaneity. But here’s the weird thing: He never gave an *equation* for it — at least not that I’ve been able to find. If anybody knows of one, I’d love to find out about it. But I have never found where he gave an explicit equation to say, “And here’s how you calculate the *degree* of non-simultaneity.” That is a puzzling thing because Einstein loved to put down the equations for little points like that — but he never did for this one.

So, [that’s] what I’m doing [in] this [slide]. Using his equation, it’s easy to come up with this slope — this time-per-distance ratio. The way you do it is, you just take two of the points using the equation he provided, and you find out, what is the difference? — what kind of rate do I have coming out of this? The net result … is that you [get] a quite simple negative relationship. So, as you, [the observer on the embankment, look] in the forward direction [at your data collected at one instance of your time], you [see] a [negative] change in time [in the simultaneously collected images of the clocks along the length of the moving train].

There’s no obvious reason why [Einstein did not write this slope equation down.] [He] had this [factor] basically *in* his equation — … [on the slide,] the factor that comes out here [in Einstein’s time translation equation] is the same factor [in my] equation. So, it’s interesting, and a little surprising, that Einstein did not do that.

This derivation gives what I call the alpha factor. (Good luck on picking out letters! Alpha seemed like a fairly safe [choice] in the context of relativity, [though] of course, [folks] use alpha in all sorts of other things, [such as] in particle physics.) The alpha factor is just this time-to-distance ratio. You measure so many [meters or] feet and you say, “What’s the time difference?” [What you] find out [is] … the *back* of the moving object … winds up being older than the *front* of the moving object.



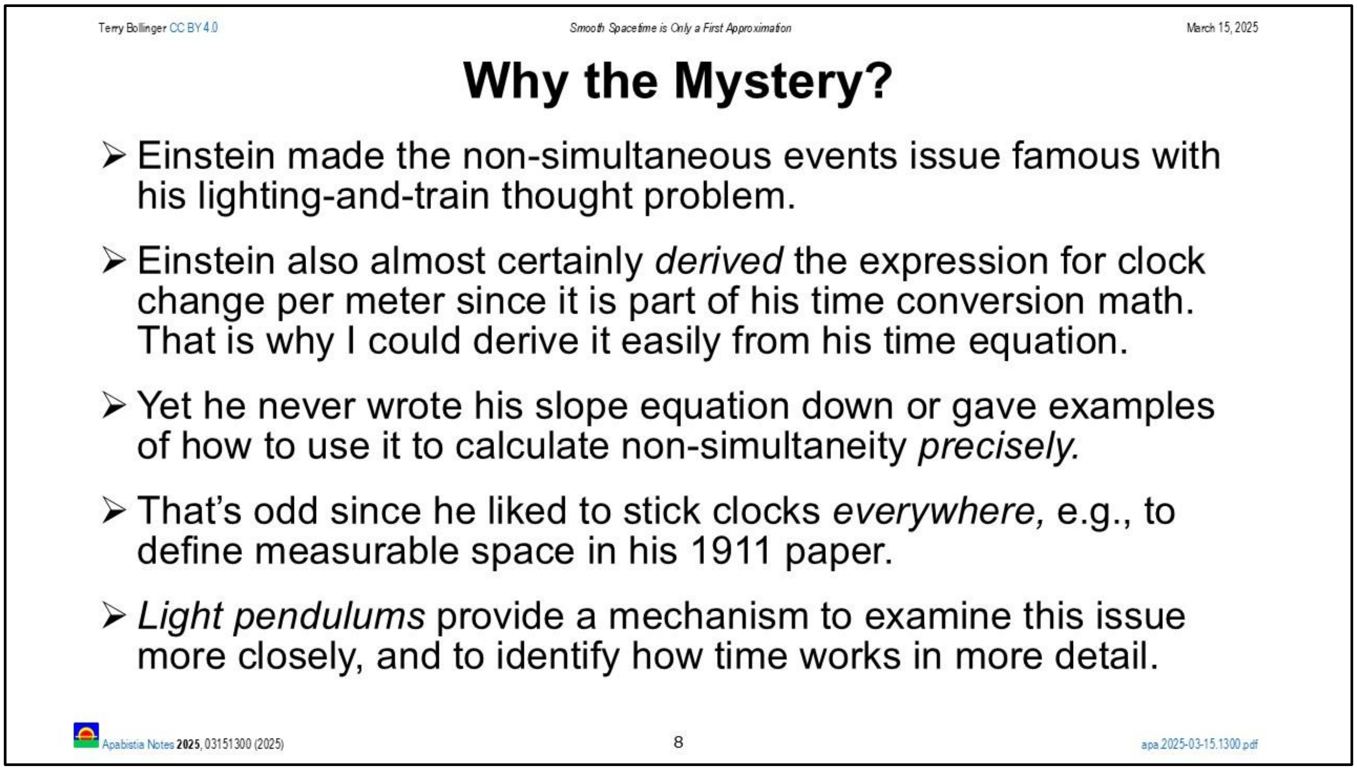
[23:40] I actually derived this [time slope earlier]. For about two years [after I first completed my derivation], I used to talk about "Einstein's missing homework" — [my implication being] that Einstein [had] *missed* this.

This is my [geometric] derivation, which is much messier. I remember [how] surprised I [was when I] went through all this… geometric work, [asking,] "What how does this work out to? What is that ratio?" When I finally came up with it — when I expressed it in terms of the coordinates of the moving object — [I found that,] if you take out the gamma factor, *it was just minus the velocity*!

So I'm thinking, like… "*What?* All *that*, and it just turns out to be *minus the velocity*?"

So yes, it was a very strange result. I *could not understand* why Einstein didn't [uncover it]. And then, I go back to his [time coordinate translation] equation [and] found he [*had* uncovered it!]. It was… buried right in the middle of his equation! He just didn't bother to pull [the time factor] out and make it into a *separate* expression.

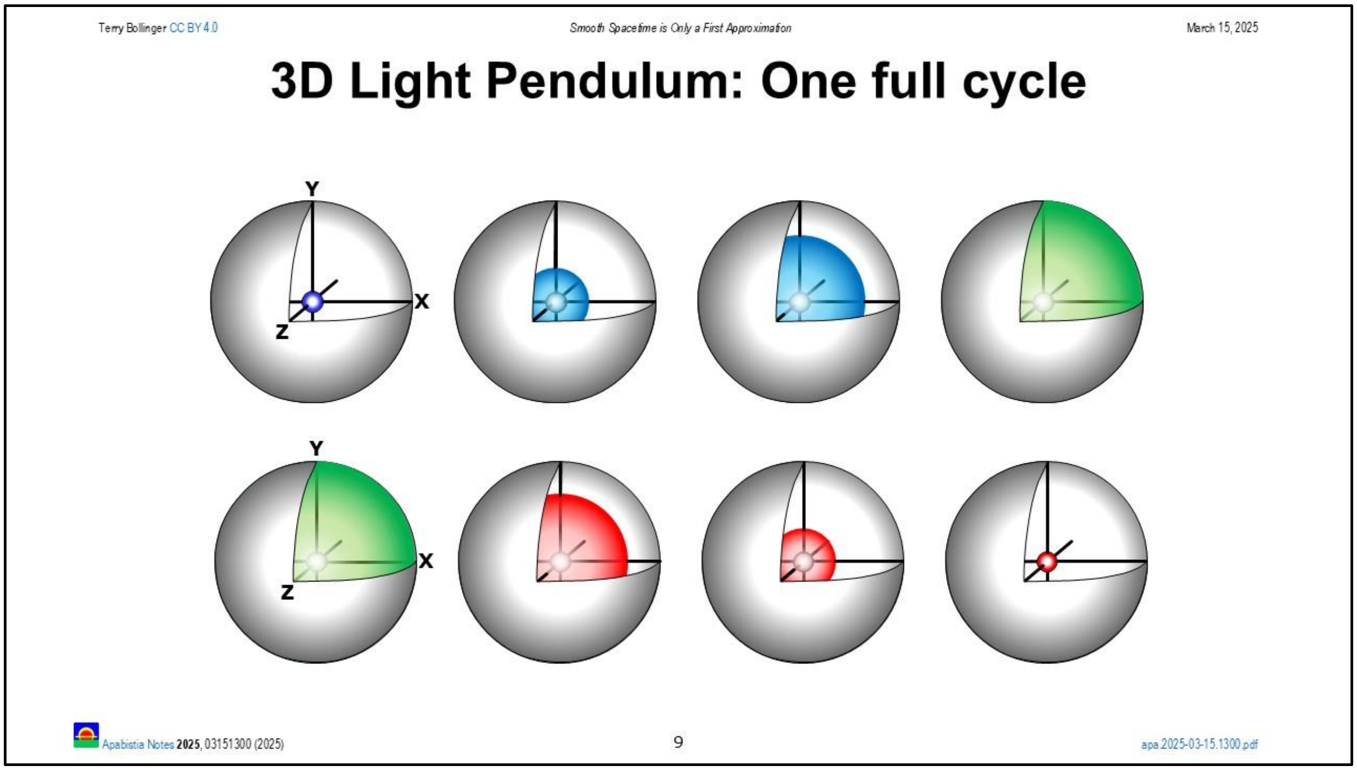
So [after coming up with] my derivation,… for two years I unfairly said that Einstein overlooked that. He didn't *overlook* it, he just never *wrote it down* — which is, in itself, interesting.



[24:49] Why was there a mystery about that? [Einstein] knew [all about this] — he was the one who [first] advertised non-simultaneity. He *had* to have derived this expression! He *had* to have known that.

He was always putting clocks on everything! He put clocks *here*, he put clocks *there*, he would have put clocks in *trains*, and [then asked], "What's the difference between the clock at the beginning of the train and [at] the end of the train?" I'm sure he would have done that. It's just the way Einstein *thought*. He always liked to explore those little nooks and crannies. But he never wrote it down.

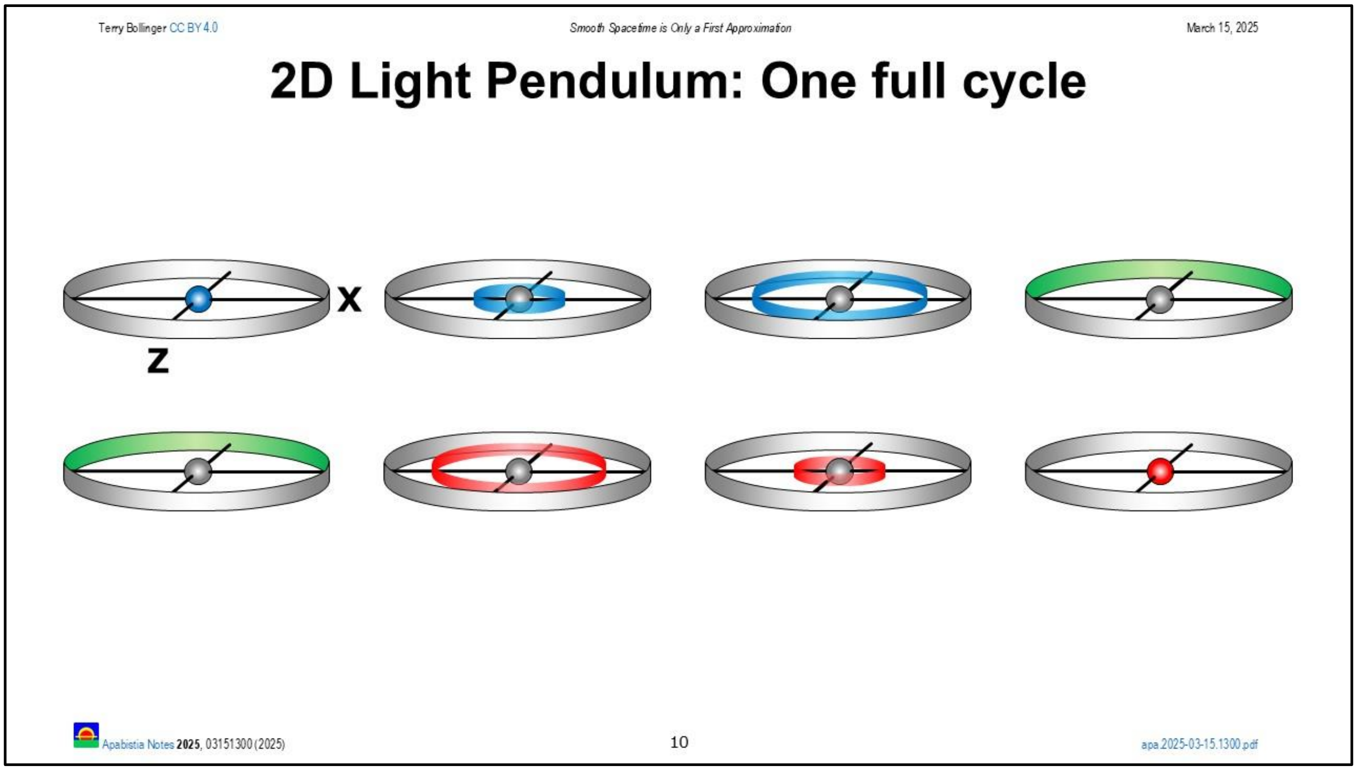
That [little mystery] gives [us] an incentive to find a mechanism [we] can [use to] explore this [issue of simultaneity] a little more carefully. The mechanism that [I've found] extremely useful for all of these problems is something called a *light pendulum*. It's just a form of clock. A lot of what I'm going to talk to now. I'm going to go through some of this fairly quickly, but I want to give people an idea [why] light clocks — light pendulums — are a very handy tool for understanding special relativity at a much deeper level than relying only on the equations.



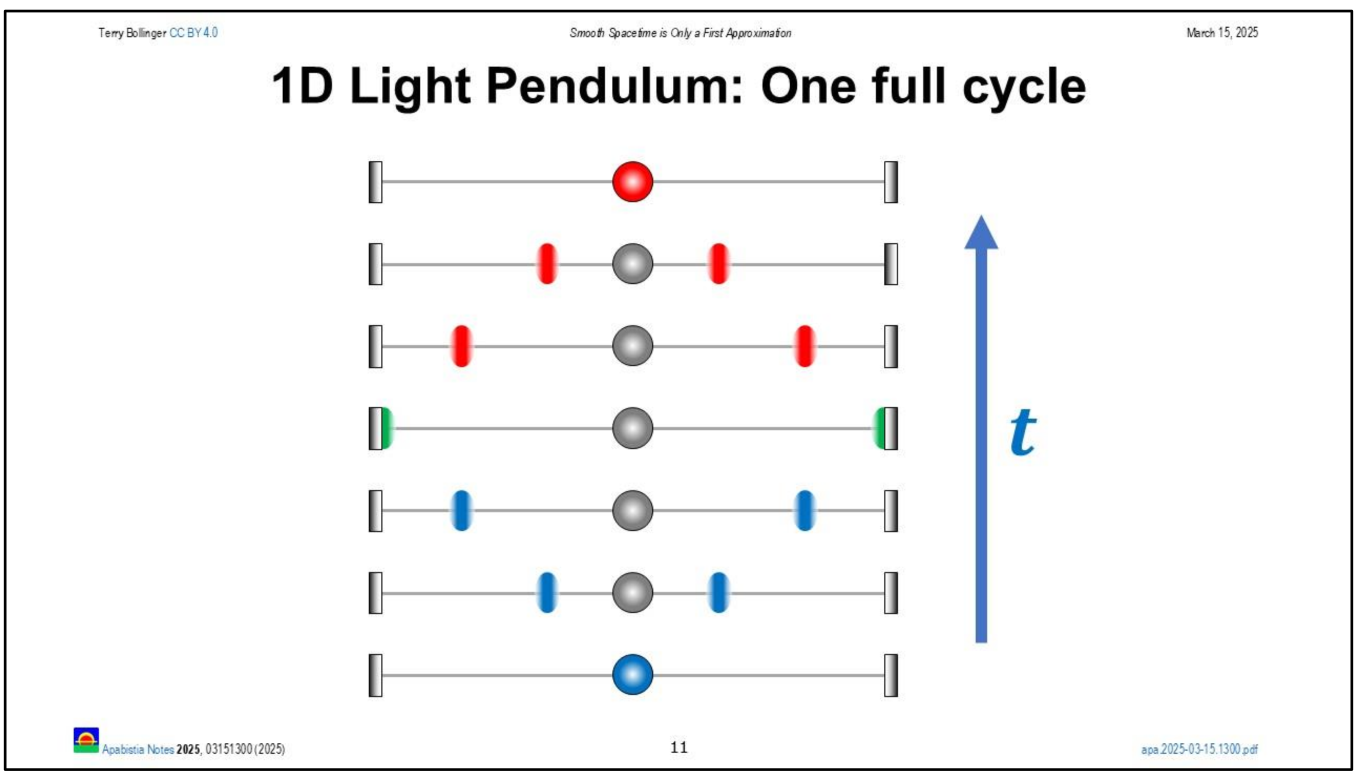
[25:51] Here's a 3D light pendulum. I like this thing! You have a light emitter at the center of [a reflective] sphere. [It emits] a pulse of light that goes out in all directions, .. bounces [off the inner surface of the sphere and] returns [to a detector co-located with the emitter at the center.] …

You calibrate [the light pendulum] so that all pulses return at the same time. When you finish calibrating, you get two things: You get measurements of distance for all three axes in three-dimensional space — [including the distances to] all points on the sphere [defined by those three axes] — and a measurement of time.

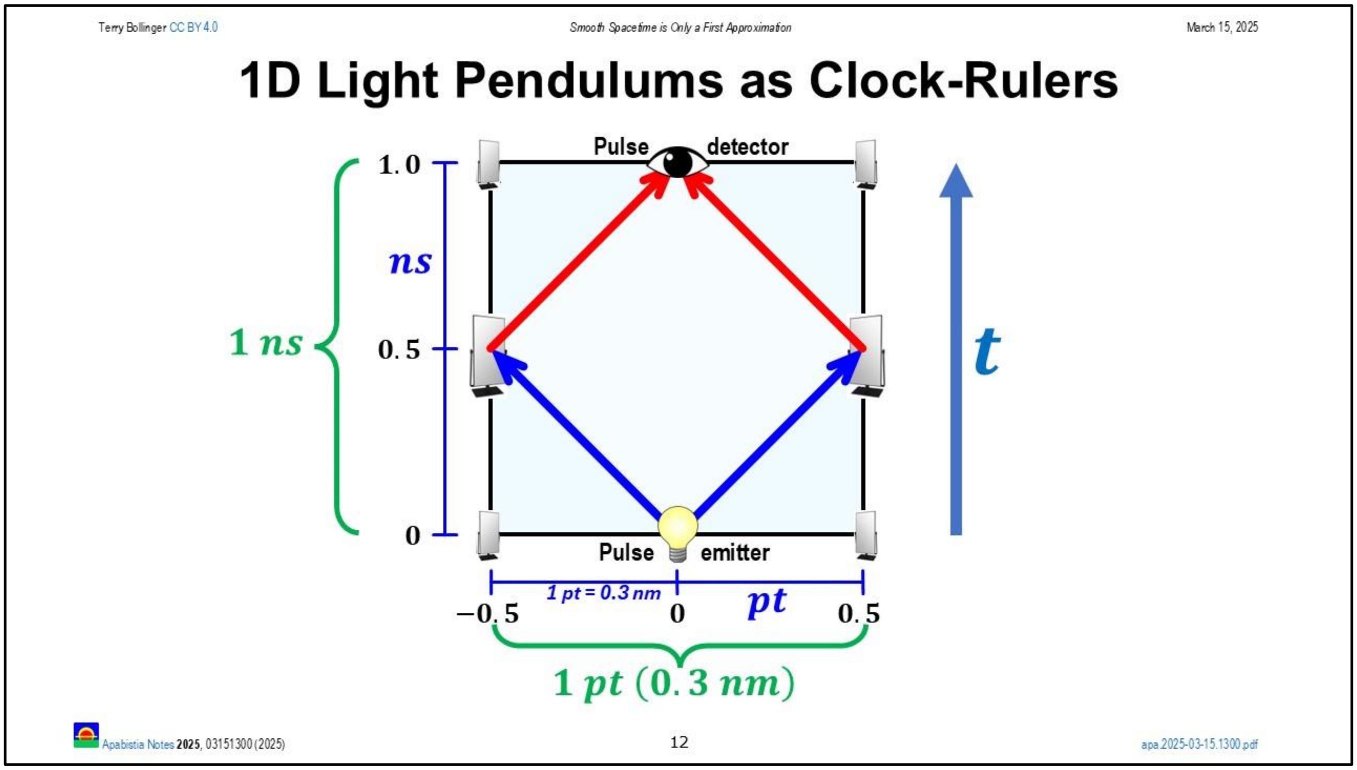
That's a marvelous little combination! It says [that] with one compact device, you can measure the concepts of space and time *simultaneously* within a single inertial frame. [This close association of distance measurement with time measurement makes] these useful test devices [for special relativity problems].



[26:44] Now, the other thing about this [device is that] since we're talking about [the one-dimensional concept of] *velocity*, you can cut the number of dimensions down to two [by ignoring one of the non-velocity axes]. [It's the] same idea, just ignoring one dimension.

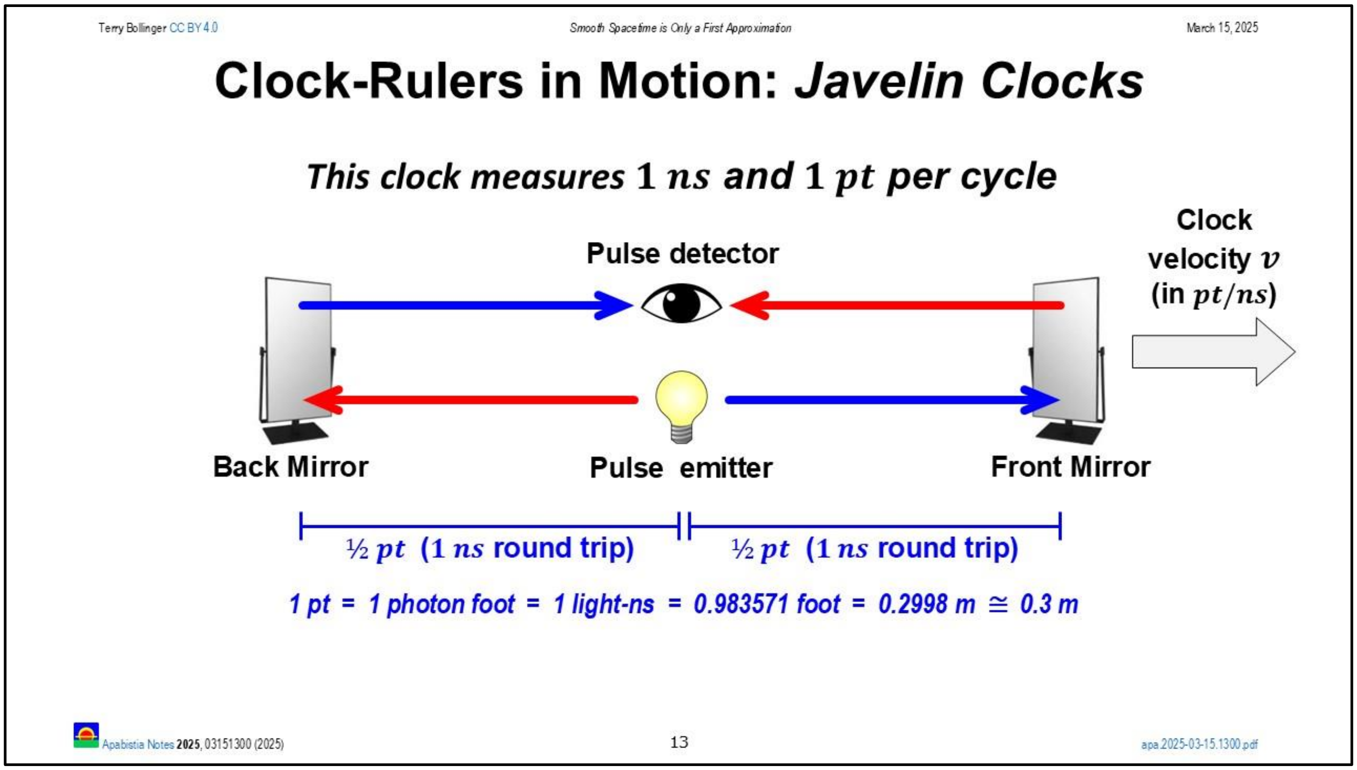


[26:56] [However,] the most *useful* [version of the light pendulum] is [when] you cut it down to *one* dimension, keeping in mind that you'll be moving this light clock in [that] particular direction. Starting at the bottom [of the figure], you have the same idea: You have *two* pulses of light [that] go out [in opposite directions,] hit mirrors, [and then] come back together [at detectors co-located with the pulse emitter].



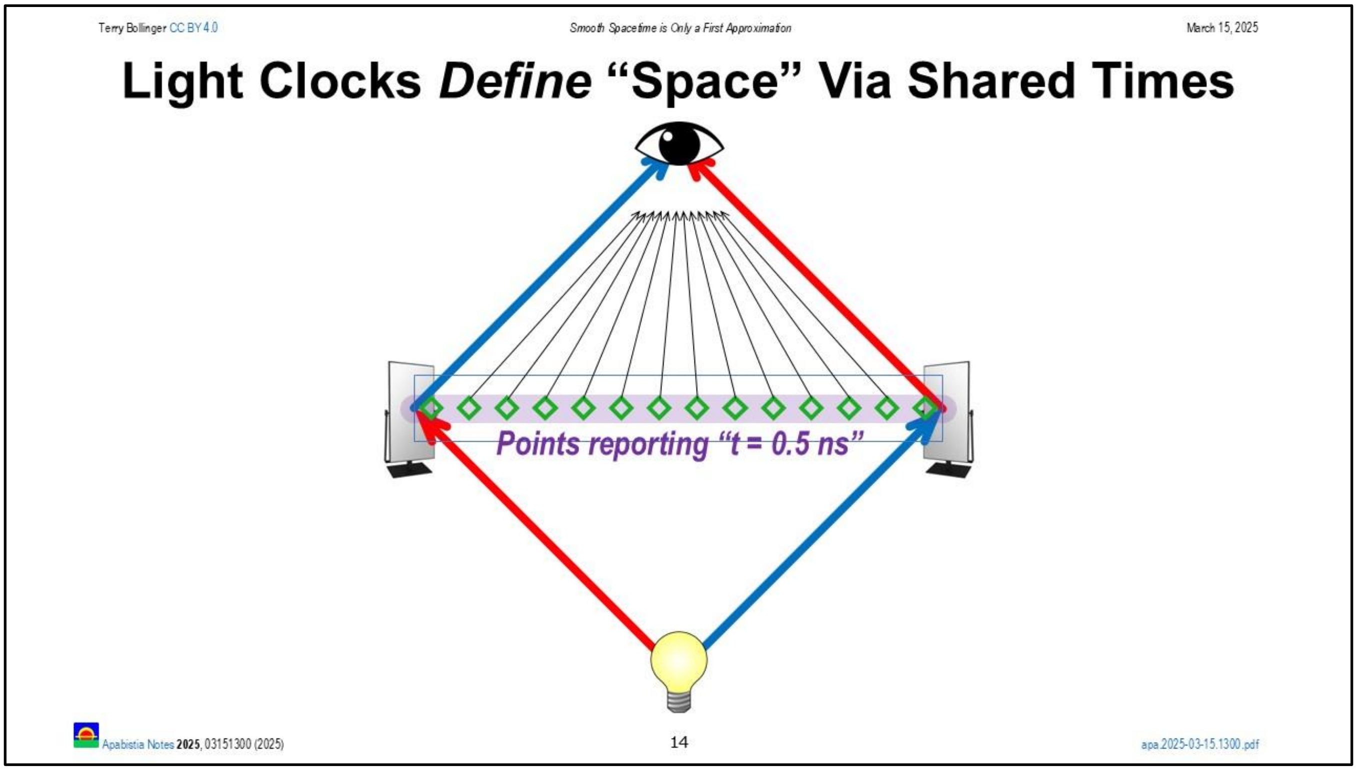
[27:14] The distance that you're covering [between the two mirrors] is a measurement of length. The unit [is something] I call a *photon foot* because it's very close to an [English system] foot. It's [also] extraordinary close to 0.3 nanometers, so that's an even better way [to think of it]. [The] abbreviation [I use] for [this unit of] one light-nanosecond [is] *pt*, for photon-foot. It doesn't matter what you call it, [it's just an] abbreviation...

[The figure shows] what [one full cycle of this clock] looks like. You have the same structure: A pulse emitter [sends out pulses] to two mirrors. [The two pulses then] come back, and you... [adjust the structure of your clock to] make sure the detections come back at the same time. [The distance between the mirrors then gives you your corresponding] measurement of length.



[28:07] This is what [the previous full-cycle figure] looks like if you compress it down into a device. My informal name for this [device] is a javelin clock. Why a javelin clock? Because it's a clock it's shaped like a rod, and you throw it [lengthwise] to the right and see what happens — [that is,] how [this motion] changes the physics of time space and time as measured by the javelin clock.

[Since] the javelin clock is also a ruler — it's a javelin clock-ruler — it makes a very interesting, simple device for testing a lot of things in special relativity.

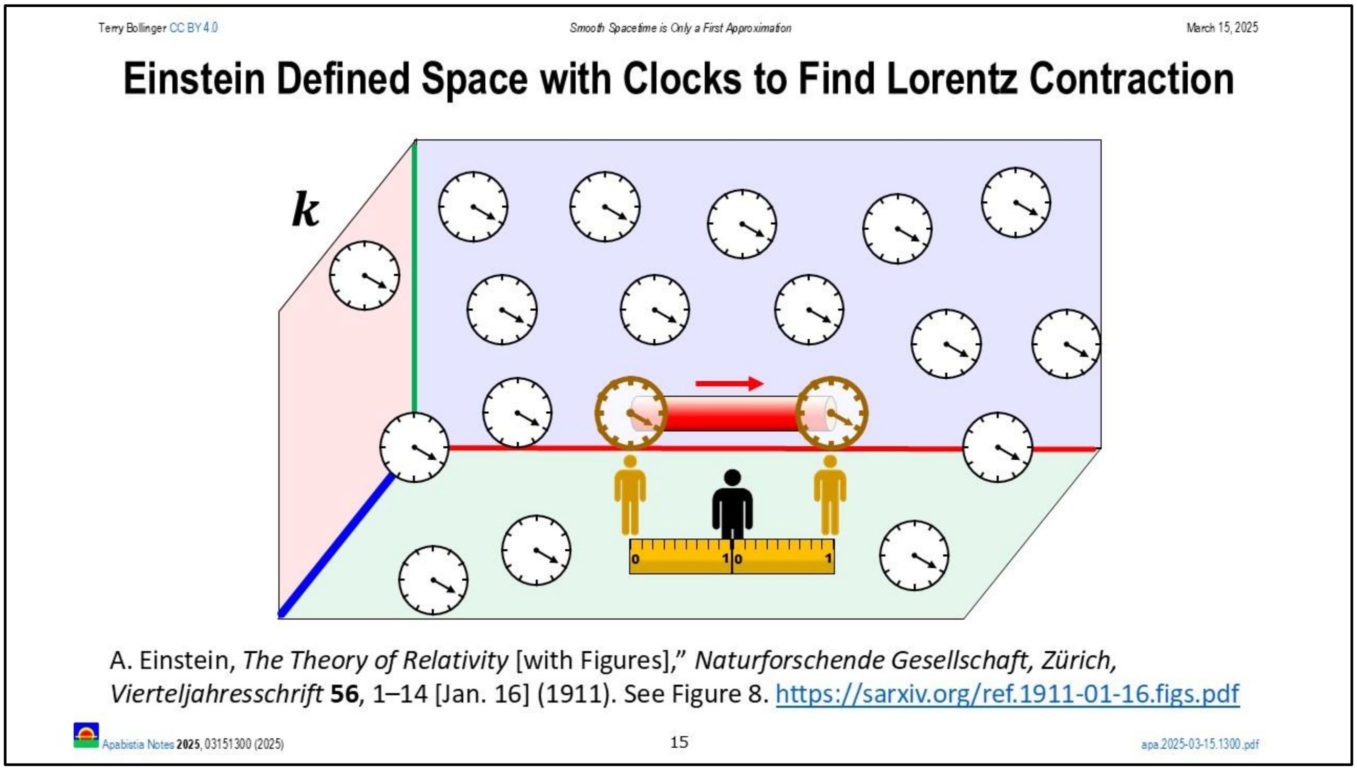


[28:48]…One thing Einstein did…was [go into] quite a bit of detail [on how] to define [space] in terms of *time*.

That seems counterintuitive! You [might well] think, "Why would you define *space* in terms of *time*?"

[The problem is that] space is, *by definition*, something that [cannot be accessed] instantaneously [at all points]. [That is because] it's orthogonal to [time]. [Since] you can't you can't touch all points [at the] same time, what you [end up doing] instead is [create a] system where you can *report* that all these points are measuring the same time. That actually winds up giving you [your only experimentally meaningful] definition of space.

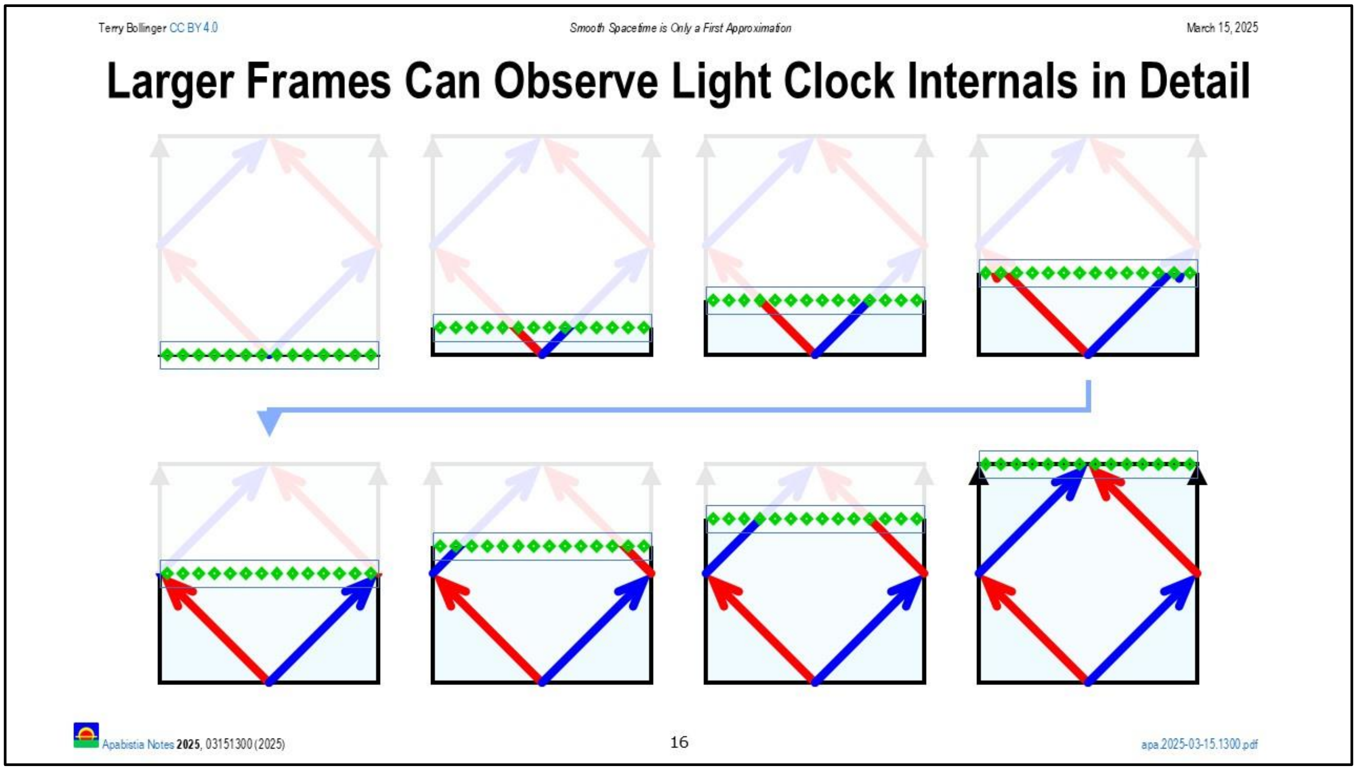
So,…the middle line [in this figure] is really your [only experimentally meaningful] definition of space for this particular light clock. The [points that define "space" in the gap] between [the two mirrors are] measured in terms of [a single question]: Do all these points report the same *time*?



[29:43] Einstein actually *did* this while deriving length contraction.… He said, "You have a whole *passel* of clocks that have been previously synchronized." (I don't show that step here, but you can go back to [my illustrated version of his 1911] paper [to see how Einstein did it].) …

So, [Einstein] has all these steps in which you start with *one* clock, you synchronize a whole *bunch* of clocks to that *one* clock, and then you send this traveling rod through [the resulting cloud of clocks]. And you say, "Hey, guys! I want you to measure at *exactly* this instant [in the future:] Where is the front [end] of that rod, [and] where is the back [end] of that rod?" And then he goes through an interesting derivation to prove that you *have to* wind up with the length of the rod being contracted.

This is a very different way from how people usually think of…it. But his actual method [for deriving length contraction] relied heavily in this concept of simultaneous time, which he had to set up *in advance*.



[30:50] In terms of analysis — and this is a simple point that's worth emphasizing, because I know I did this for years myself — when people think of two different inertial frames, it's easy to [slip into] thinking of the moving object is having its own [version] of "space" [in which] it lives — that, you know, it has its *own* definition of [space] and time — which is absolutely true!

[But from that true statement,] it's easy to [infer incorrectly] that you can't get *into* that [separate] definition [— that you cannot watch its inner details and dynamics unfold in real-time from *your* space and time perspective].

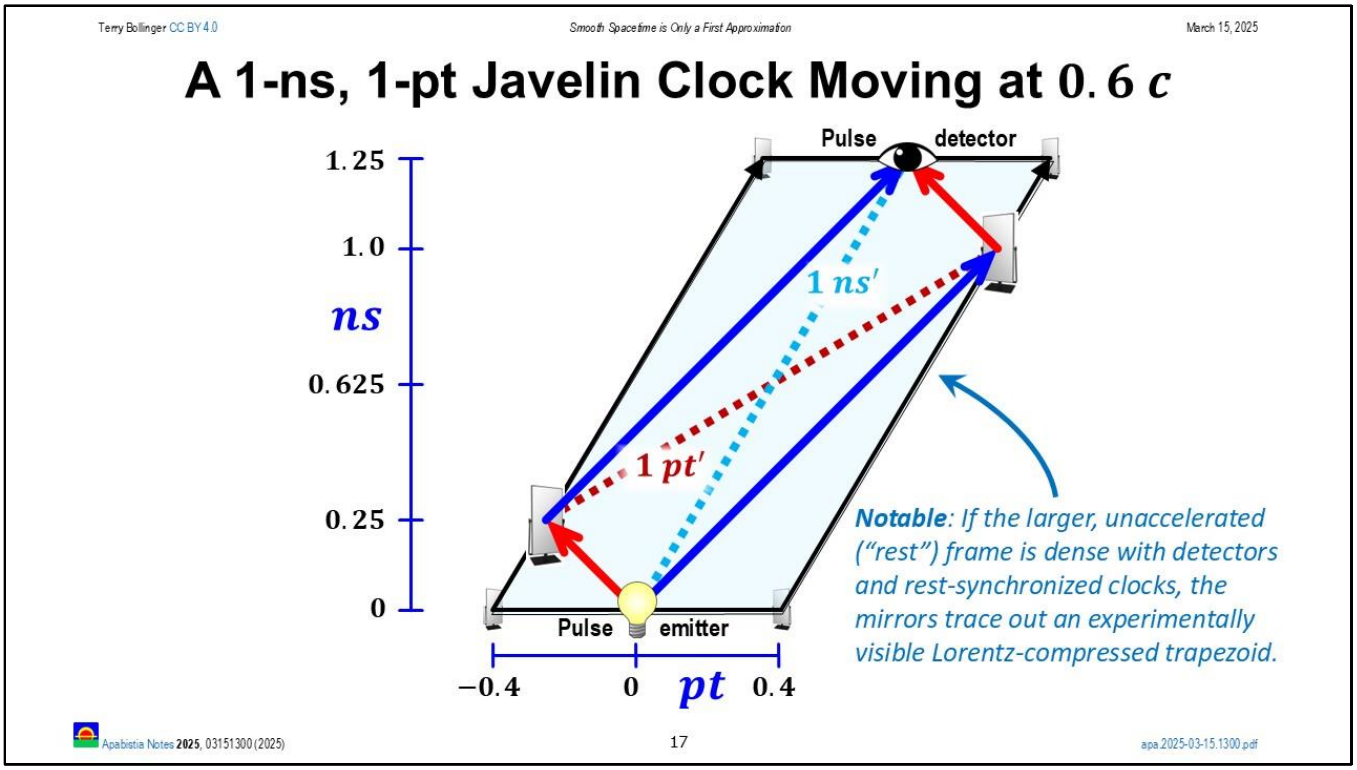
That is *false*. That is *completely false*.

You can *scan the daylights* out of [clocks and objects in that other frame] — you can watch *every step* of what happens in the object [and the mechanical internals of all of its clocks by] using [*your*] definition of space and clocks in [*your*] space. [You can always instrument your viewpoint to indefinite detail and then use it to] analyze and say, [for example,] "Well, where's the lightning now? Where's the lightning now?"

So, [you] have this [ability to perform] constant observation. It means that you can [look at] someone else's light clock — someone else's [moving] javelin clock — and you can *analyze* it in great detail and say, "How does this thing *look* at a particular moment in [*my* space and] time?"

If you [instead] use the abstraction [that] says, "Well, that's just a boosted frame… and I'm in this frame… and never-the-two-shall-meet. — that doesn't *tell you* anything. That's another reason why you won't see Minkowski space showing up in this [analysis]. I'm just using ordinary, [flat, four]-dimensional [spacetime] because that's the space that in which you can [collect data and] *do analysis*. If you use the Minkowski [spacetime] representation, you're [pulling] yourself *away* from [the ability to collect and analyze real-time data in your] analysis.

What you want [instead is a way to] say, "How do the *data* compare? What's the *actual* comparison between these?" So, you can do a *scan*, just like a like a raster scan of some object — like a LIDAR [(light radar) scan — though in this case, the secret to obtaining a solid, detailed scan is to avoid the ambiguities of moving light entirely and focus instead on creating a dense cloud of unmoving (in your frame) sensors and clocks, all synchronized to your inertial frame's definition of time. Bubble and cloud chamber are examples of such high-density clock-and-sensor scanners for analyzing fast-moving objects, though they only scan point-like objects such as muons that lack details about the spatial relationships between clocks and rulers. That is why javelin clocks that use human-scale clock internals are better for providing detailed information about the relationships between time and space in special relativity].



[32:30] Now, what happens if you move a javelin clock at a fast speed? [This figure] is an exact representation of what happens if you move a javelin clock at 0.6 c, which is the same as $\beta = 0.6$ — units of c [or] beta, it's the same thing.

So, you have your [pulse] emitter down at the bottom. You have your mirrors, [shown] at which the points where [they] reflect the beam [pulses]. [Finally,] you have a detector at the top.

Notice [also that] you've got Lorentz contraction. Down at the bottom, [this clock's] original [length] of 1 pt (0.3 nanometers) is now 0.8 pt [(0.24 nanometers)]. So, you have a Lorentz contraction going on here [— that is, you must divide the rest-frame length by the Lorentz factor.]

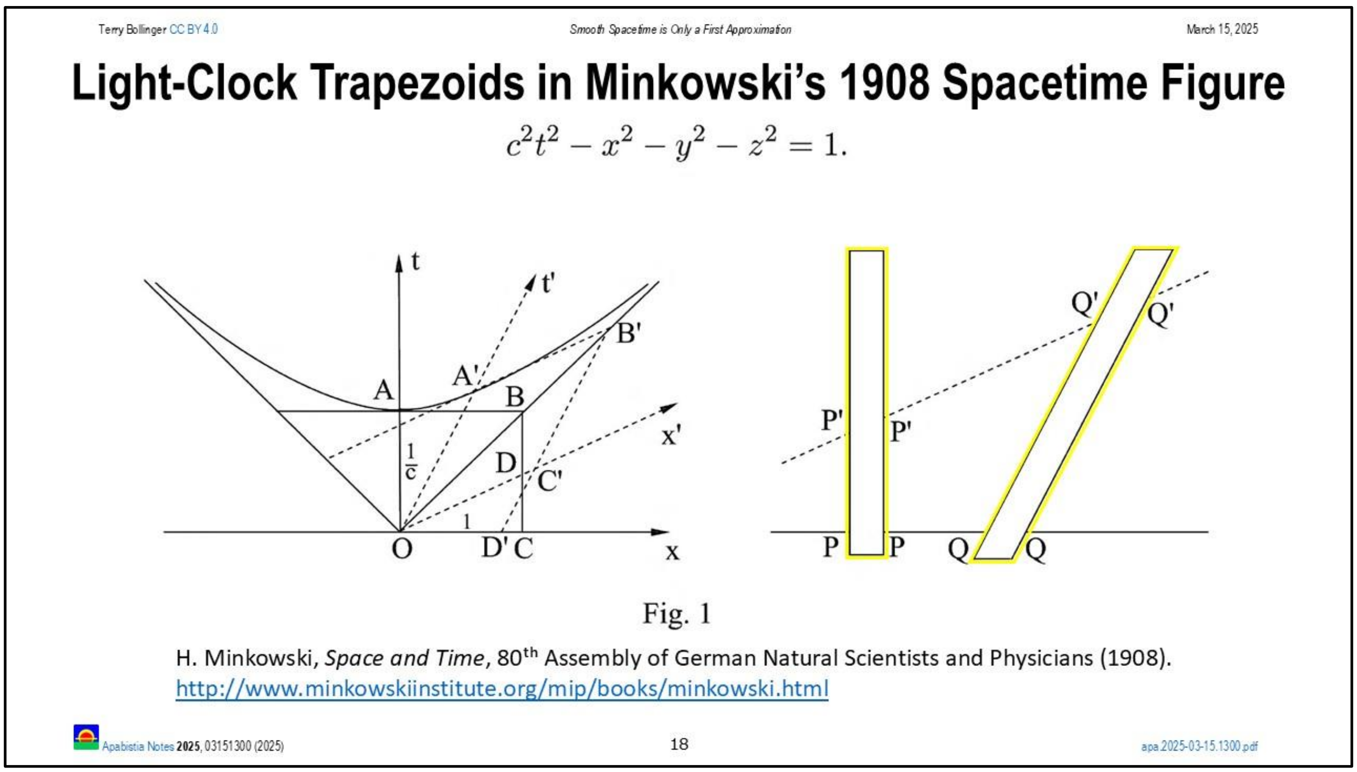
Also notice that when the [sensor] eye at the top [finally] sees [both light pulses return to complete one light cycle, the duration of that cycle [from the perspective of the larger] observer frame is multiplied by the] Lorentz factor. [Thus] you've [also] got a time dilation: [One cycle of the moving clock has] been stretched out a little bit.

Now, the point [I want to] emphasize is that once you accelerate a javelin clock, [it slows down *immediately*]. This is why I say there's no ambiguity about when the time dilation occurs: It begins *instantly*. The clock *simply runs slower*. Any analysis you do is going to say, "That clock is running slower!"

Why? Because the [forward-moving] light [is in a race with the fast-fleeing forward mirror, and thus] has to go farther before it can get [reflect from the front mirror and get] back [to the sensor]. You [can] see that [the] blue [arrows, which show light moving] forward, are just going to take more time. There's nothing exotic about this. An accelerated system embedded in larger system is going to go slower in time [as defined by the larger system.]

[If you were wondering,] yes, you [still] have Poincaré symmetries. I'll get into how those *still apply* [later]. But [the point here is that] you have to be careful about the constraints [on where and how those symmetries apply.]

The other thing I want you to notice is [that in this figure,] that [slanted] brown line represents space as [observed and] defined by the person [moving with] the javelin clock [for any particular moment of *their* time]. [The traveler's] time is defined by that blue line. So, both of those [lines] are slanted [relative to the encompassing observer frame, meaning.] So, you're [never] going to get a *single* view of the [smaller system's] space representation. [At any one moment in your larger-frame time,] you're [only] going to [see] a [thin] slice of [space as defined by the traveler [for a particular moment in that traveler's time], and] that [slice you see] is going to vary by [your definition of] time.

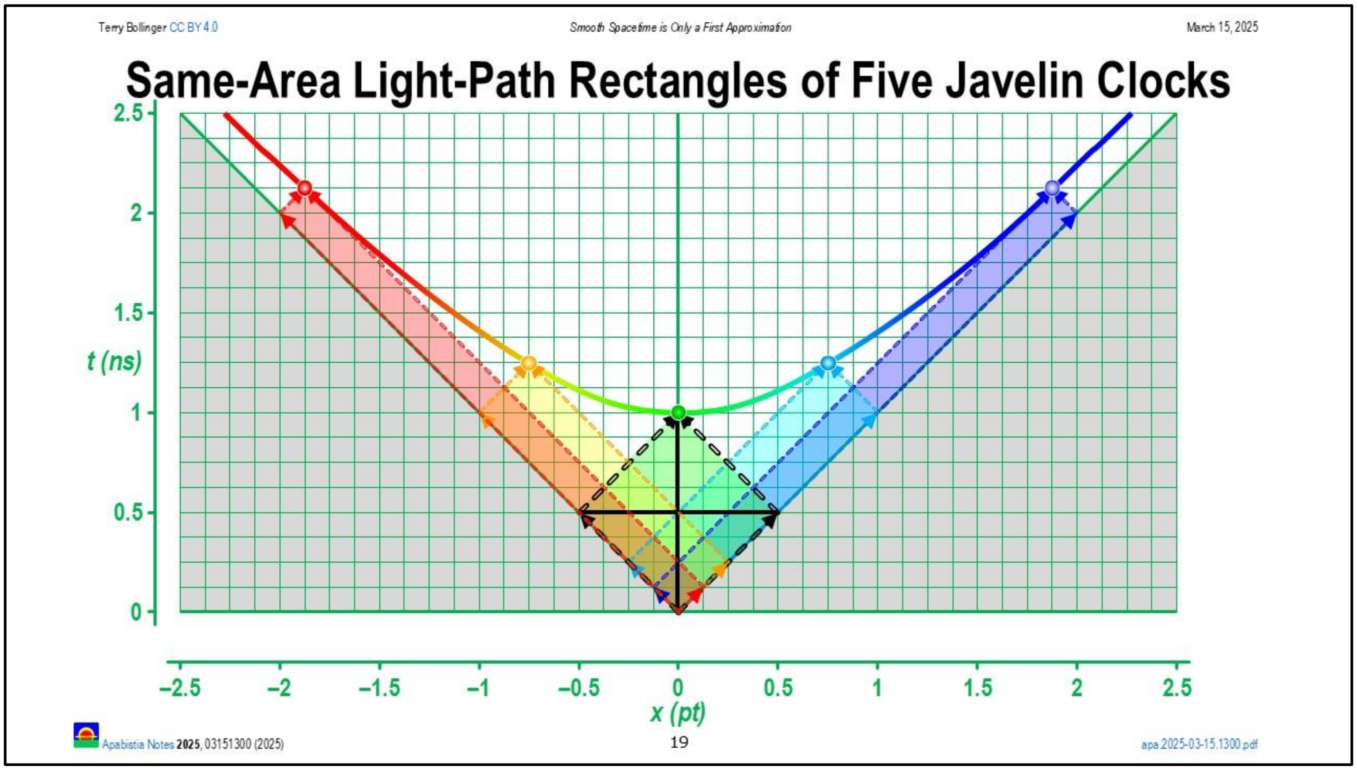


[34:56] The other thing I want to point out is [that rectangles and trapezoids traced out by static and moving light clock mirrors are] *not* new figures. [As you can see in this figure from his *Space and Time* lecture,] Minkowski [came up with the same rectangular and trapezoidal shapes] in 1908. If you look especially at the trapezoid on the right — [the one] with the two Qs at the bottom — that is the *same* [kind of trapezoid as in the javelin clock example].

You can, [of course,] get into [a lot more] details about how [to derive and] represent [such trapezoids. [For example, Minkowski] does not show the light paths that I have shown. But this [figure summarizes] how he derived [his version of length-duration trapezoids], [and shows how he] came up with the same geometry.

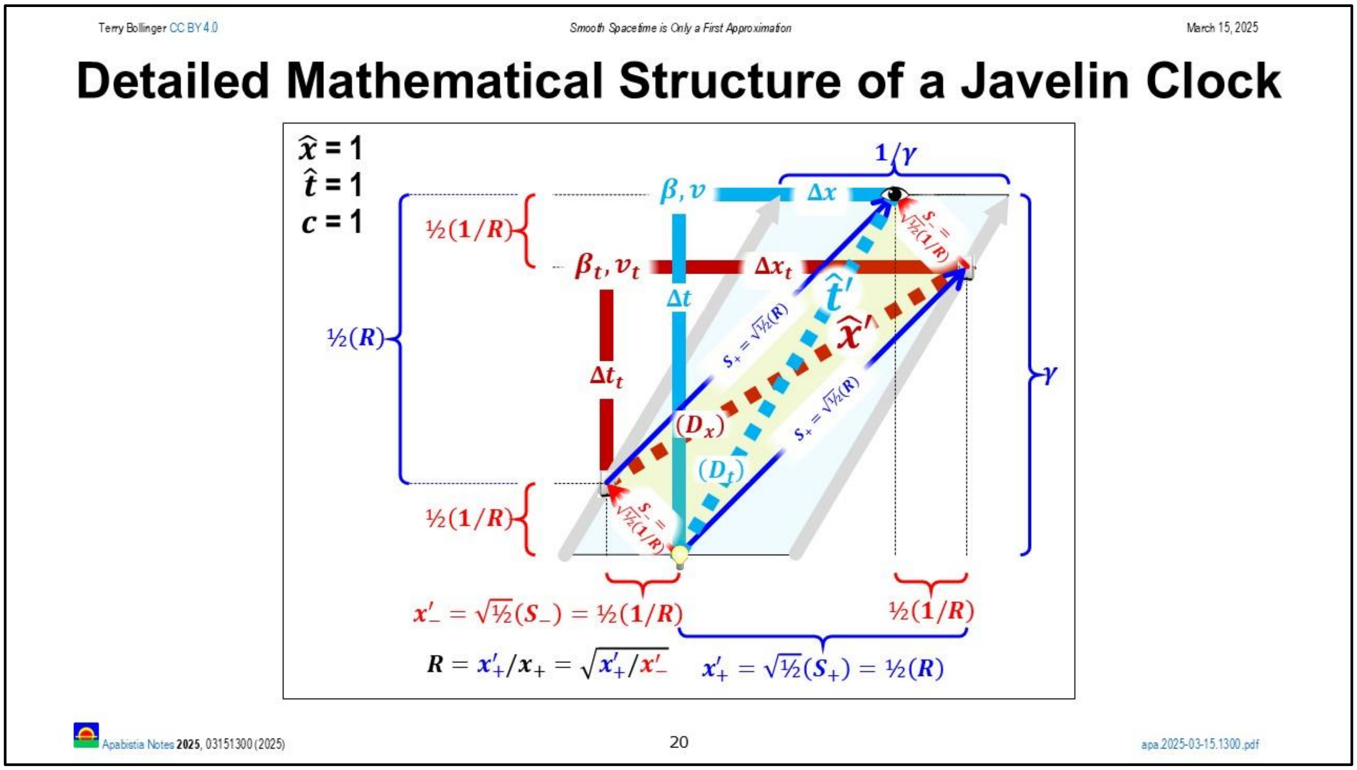
So, [light-clock trapezoids are] actually an old concept, but you have to you have to elaborate a little bit on [Minkowski's older version of such trapezoids] to make [them] more experimentally [meaningful].

The [rectangle and trapezoid pair in the Minkowski illustration is also an] interesting example of [how] these trapezoidal shapes [are the] distorted outlines [of the rectangular time paths of a javelin clock at rest.] You get [the distorted trapezoidal clock outline] when you [move that same] javelin clock at a high velocity.



[35:41] In fact, if you look at the light paths instead of the mirror paths, you get this beautiful [hyperbola] which, if you look back, is the same [hyperbola] that Minkowski drew. And you get these little areas, these little regions, that show the lines traced out by the light path.

I'll tell you another interesting little feature of these: Every one of those rectangular areas has exactly the same area. This is actually an invariant in special relativity. The [durations] times [the] distances on these areas remains invariant no matter how fast you are going… As [you] extend out [this family of rectangles in both velocity directions, you get… the same lovely [hyperbola] that you get from Minkowski's work.



[36:33] [This figure gives all the] details…of how [a javelin clocks] works, [and its associated] units. It gets a bit messy, and I'm certainly not going to go through that. However, I will point out one number here, called R.

R is the *relativistic Doppler factor* — [a name] I found out [about] belatedly. When I [first encountered this number in my figures], I called it the *forward light path ratio*. [By that, I meant the] ratio of how far light travels to get to the [forward mirror] in [a moving] system versus how far light travels [forward for the same system at rest].…

This [ratio of forward light paths] turns out to be [an especially important] number…for figuring out how [space and time] work [in light clocks].

But it is also something called the *relativistic Doppler factor*. I was going through some materials [related to quasar jets] and, lo and behold, there was the exact same equation I'd been using for the for the forward [light path] ratio!

So, [the] relativistic Doppler factor is an important number. [In fact, for reasons I will explain later,] I would argue that it's *more* fundamental than the Lorentz contraction [factor and] mechanism.

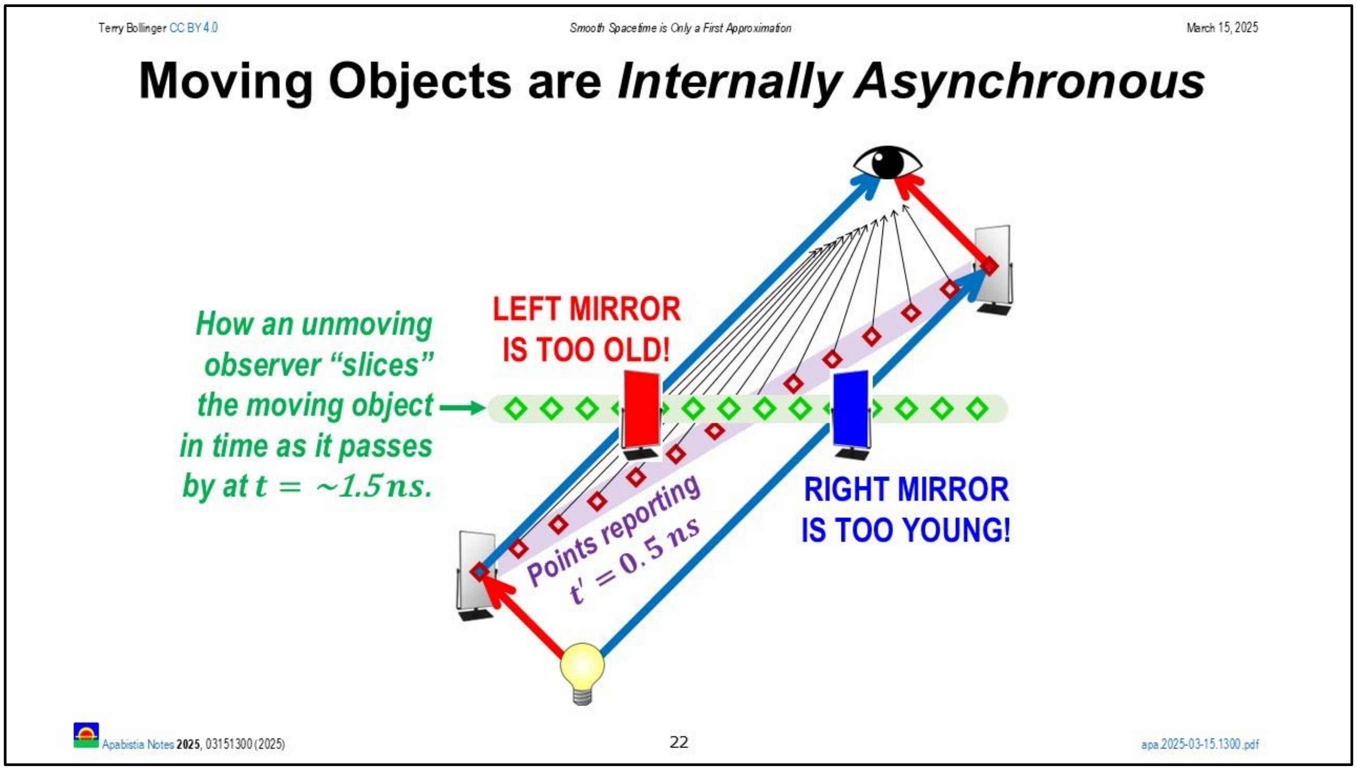
Special Relativity Conversions [Bollinger]

	Velocity	Unitless Velocity	Forward Light Paths Ratio (Relativistic Doppler Factor)	Rapidity	Binary Rapidity	Lorentz Factor	Diagonal Factor	Age Gradient	Traveler's Gradient	In-Frame Gradient
	$v =$	$\beta =$	$R =$	$w =$	$\rho =$	$\gamma =$	$D =$	$\alpha =$	$\alpha_+ =$	$\alpha' =$
Best→	v	$\frac{v}{c}$	$\sqrt{\frac{1+\beta}{1-\beta}}$	$\ln R$	$\log_2 R$	$\frac{R+R^{-1}}{2}$	$\sqrt{2\gamma^2-1}$	$-\frac{\beta\gamma}{c}$	$-\alpha$	$-\frac{v}{c^2}$
Given↓ v	v	$\frac{v}{c}$	$\sqrt{\frac{c+v}{c-v}}$	$\ln\sqrt{\frac{c+v}{c-v}}$	$\log_2\sqrt{\frac{c+v}{c-v}}$	$\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$	$\sqrt{\frac{c^2+v^2}{c^2-v^2}}$	$-\frac{v}{c\sqrt{c^2-v^2}}$	$\frac{v}{c\sqrt{c^2-v^2}}$	$-\frac{v}{c^2}$
β	$c\beta$	β	$\sqrt{\frac{1+\beta}{1-\beta}}$	$\ln\sqrt{\frac{1+\beta}{1-\beta}}$	$\log_2\sqrt{\frac{1+\beta}{1-\beta}}$	$\frac{1}{\sqrt{1-\beta^2}}$	$\sqrt{\frac{1+\beta^2}{1-\beta^2}}$	$-\frac{\beta}{c\sqrt{1-\beta^2}}$	$\frac{\beta}{c\sqrt{1-\beta^2}}$	$-\frac{\beta}{c}$
R	$c\frac{R-R^{-1}}{R+R^{-1}}$	$\frac{R-R^{-1}}{R+R^{-1}}$	R	$\ln R$	$\log_2 R$	$\frac{R+R^{-1}}{2}$	$\sqrt{\frac{R^2+R^{-2}}{2}}$	$-\frac{R-R^{-1}}{2c}$	$\frac{R-R^{-1}}{2c}$	$-\frac{R-R^{-1}}{2c}$
w	$c\frac{e^w-e^{-w}}{e^w+e^{-w}}$	$\frac{e^w-e^{-w}}{e^w+e^{-w}}$	e^w	w	$\frac{w}{\ln 2}$	$\frac{e^w+e^{-w}}{2}$	$\sqrt{\frac{e^{2w}+e^{-2w}}{2}}$	$-\frac{e^w-e^{-w}}{2c}$	$\frac{e^w-e^{-w}}{2c}$	$-\frac{e^w-e^{-w}}{2c}$
ρ	$c\frac{2^\rho-2^{-\rho}}{2^\rho+2^{-\rho}}$	$\frac{2^\rho-2^{-\rho}}{2^\rho+2^{-\rho}}$	2^ρ	$\rho\ln 2$	ρ	$\frac{2^\rho+2^{-\rho}}{2}$	$\sqrt{\frac{2^{2\rho}+2^{-2\rho}}{2}}$	$-\frac{2^\rho-2^{-\rho}}{2c}$	$\frac{2^\rho-2^{-\rho}}{2c}$	$-\frac{2^\rho-2^{-\rho}}{2c}$
γ	$c\sqrt{1-\frac{1}{\gamma^2}}$	$\sqrt{1-\frac{1}{\gamma^2}}$	$\sqrt{\frac{\gamma+\sqrt{\gamma^2-1}}{\gamma-\sqrt{\gamma^2-1}}}$	$\ln\sqrt{\frac{\gamma+\sqrt{\gamma^2-1}}{\gamma-\sqrt{\gamma^2-1}}}$	$\log_2\sqrt{\frac{\gamma+\sqrt{\gamma^2-1}}{\gamma-\sqrt{\gamma^2-1}}}$	γ	$\sqrt{2\gamma^2-1}$	$-\frac{\sqrt{\gamma^2-1}}{c}$	$\frac{\sqrt{\gamma^2-1}}{c}$	$-\frac{\sqrt{\gamma^2-1}}{c}$
D	$c\sqrt{\frac{D^2-1}{D^2+1}}$	$\sqrt{\frac{D^2-1}{D^2+1}}$	$\sqrt{\frac{1+\sqrt{\frac{D^2-1}{D^2+1}}}{1-\sqrt{\frac{D^2-1}{D^2+1}}}}$	$\ln\sqrt{\frac{1+\sqrt{\frac{D^2-1}{D^2+1}}}{1-\sqrt{\frac{D^2-1}{D^2+1}}}}$	$\log_2\sqrt{\frac{1+\sqrt{\frac{D^2-1}{D^2+1}}}{1-\sqrt{\frac{D^2-1}{D^2+1}}}}$	$\sqrt{\frac{D^2+1}{2}}$	D	$-\sqrt{\frac{D^2-1}{2c^2}}$	$\sqrt{\frac{D^2-1}{2c^2}}$	$-\sqrt{\frac{D^2-1}{2c^2}}$
α	$-\frac{\alpha c^2}{\sqrt{1+\alpha^2c^2}}$	$-\frac{\alpha c}{\sqrt{1+\alpha^2c^2}}$	$\sqrt{\frac{\sqrt{1+\frac{1}{\alpha^2c^2}}+1}{\sqrt{1+\frac{1}{\alpha^2c^2}}-1}}$	$\ln\sqrt{\frac{\sqrt{1+\frac{1}{\alpha^2c^2}}+1}{\sqrt{1+\frac{1}{\alpha^2c^2}}-1}}$	$\log_2\sqrt{\frac{\sqrt{1+\frac{1}{\alpha^2c^2}}+1}{\sqrt{1+\frac{1}{\alpha^2c^2}}-1}}$	$\sqrt{1+\alpha^2c^2}$	$\sqrt{1+2\alpha^2c^2}$	α	$-\alpha$	$\frac{\alpha}{\sqrt{1+\alpha^2c^2}}$
α_+	$\frac{\alpha_+c^2}{\sqrt{1+\alpha_+^2c^2}}$	$\frac{\alpha_+c}{\sqrt{1+\alpha_+^2c^2}}$	$\sqrt{\frac{\sqrt{1+\frac{1}{\alpha_+^2c^2}}+1}{\sqrt{1+\frac{1}{\alpha_+^2c^2}}-1}}$	$\ln\sqrt{\frac{\sqrt{1+\frac{1}{\alpha_+^2c^2}}+1}{\sqrt{1+\frac{1}{\alpha_+^2c^2}}-1}}$	$\log_2\sqrt{\frac{\sqrt{1+\frac{1}{\alpha_+^2c^2}}+1}{\sqrt{1+\frac{1}{\alpha_+^2c^2}}-1}}$	$\sqrt{1+\alpha_+^2c^2}$	$\sqrt{1+2\alpha_+^2c^2}$	$-\alpha_+$	α_+	$-\frac{\alpha_+}{\sqrt{1+\alpha_+^2c^2}}$
α'	$-\alpha'c^2$	$-\alpha'c$	$\sqrt{\frac{1-\alpha'c}{1+\alpha'c}}$	$\ln\sqrt{\frac{1-\alpha'c}{1+\alpha'c}}$	$\log_2\sqrt{\frac{1-\alpha'c}{1+\alpha'c}}$	$\frac{1}{\sqrt{1+\alpha'^2c^2}}$	$\sqrt{\frac{1+\alpha'^2c^2}{1-\alpha'^2c^2}}$	$\frac{\alpha'}{\sqrt{1-\alpha'^2}}$	$-\frac{\alpha'}{\sqrt{1-\alpha'^2}}$	α'

[37:55]…If you *really* want to go through *all* the details, this is a [table] I [have] available on my website. [It includes] all the different conversions you can do between these [special relativity] factors, [including:] the relativistic Doppler factor; [two versions of a] factor called *rapidity* [that] is also a very interesting, [with each version consisting of a] different log [base] of the relativistic Doppler factor and [*binary rapidity* being my version;] …I've also got the age gradient, which essentially is a version of velocity; and two variants of [the age gradient] that can be useful for practical purposes [such as] trying to measure [outside time flows from] inside of a [moving] system. [For example, if] you're [in a ship] traveling in a [larger] system, the traveler's gradient is a little easier to use [to calculate how destination time changes (blueshifts) in front of you].

So, this [set of conversions] is massive overkill, but they're all pretty well checked out. There's a Google equations version of [the table] if you actually want to…try some of these.

So, [there are] a lot of different factors you can bring up [and use], with *R* being a particularly important one.



[38:54] Now, in some ways this is just ridiculously obvious because Einstein already pointed it out. Yes, if objects are seen as being asynchronous, it also means the object *itself* is a synchronous with the outside world. So, if the train sees the lightning flashes as being asynchronous, then if somebody looks [inside] the train [as it passes by], guess what? If you analyze the train in terms of lightning flashes, you will find out that the *train* is asynchronous.

And yet, we tend not to think of it that way. Our minds jump *instantly* to a different viewpoint. We want to *become* the observer in the train and say, "Well, from *inside* the train, it's fine."

Yes, you can do that — but if you do, it doesn't *help*, because you've immediately lost the analytical aspect of saying, "Well, what *actually* happens [is]…", because anytime you jump [between observers], you've got to be very, very careful. People do that when they cross black hole [event horizons] — they always instantly jump between one observer perspective and another. [That's] always dangerous in mathematical analysis to jump instantaneously without thinking about it from one viewer to another viewer. You don't want to do that [because] it destroys the ability to analyze.

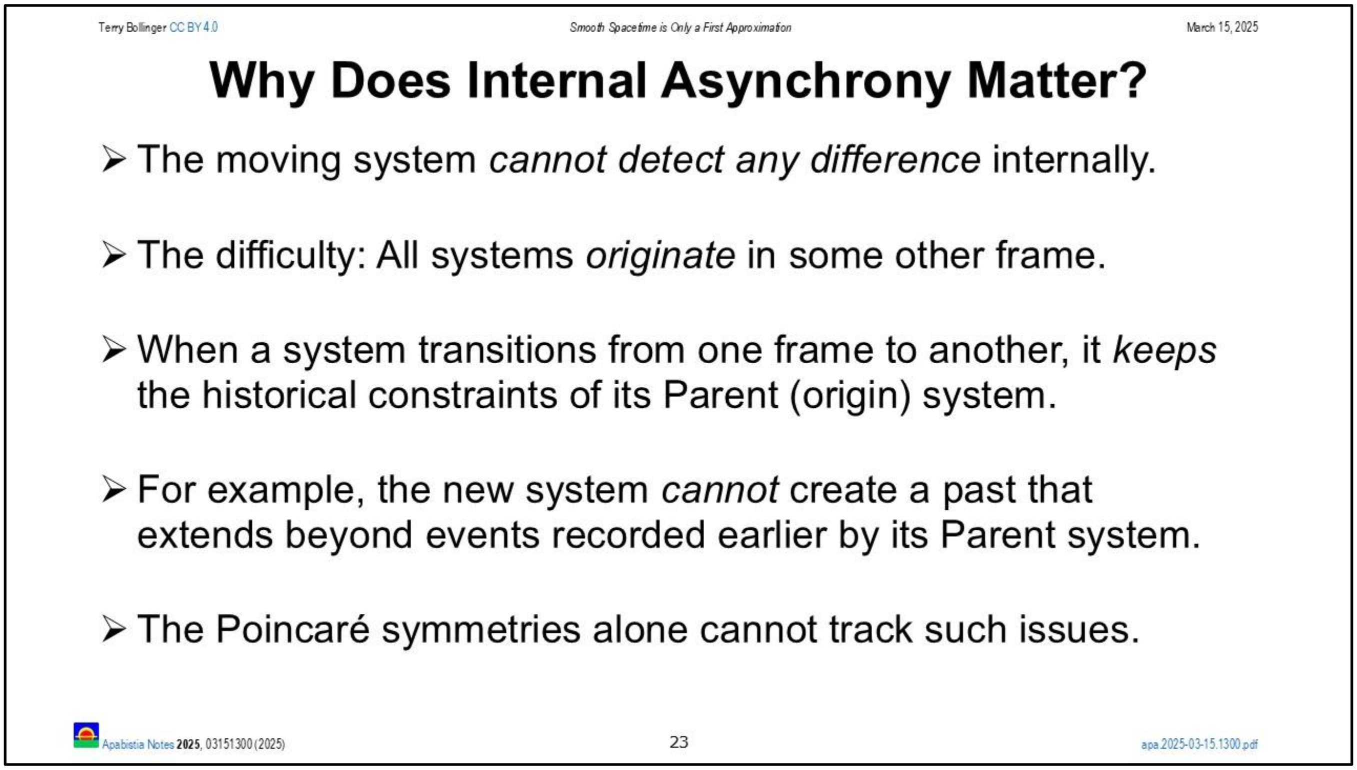
So, if we go back to the simple realization that this clock is *fully within* our space — all the parts are there, it's going by, it's whizzing through an actual system. If it's a train, it's on tracks, so that's an obvious one there, [since] if you got a Lorentz compress-compressed train, it's still riding on the same tracks, and those tracks still have time attached from our system. So, [it's the] same thing here. You can always analyze these, and when you do, you discover that the object *is not synchronous with itself*.

So, if you some watch somebody's head going by at near the speed of light, you would discover that the front of their head is ahead in time compared to the back of their head. There's something about that just doesn't [sound right]. We don't want to think that way. [We] can't imagine being an observer *and* being asynchronous with [our] own minds. Yet that is exactly what the physics tells us — that, in terms of [any] analysis from an outside observer, you see this as an *asynchronous* system.

And [thus] you find out that the *right* mirror is too *young*, and the *left* mirror is too *old*.

[This is where] I think we're [getting] into why Einstein possibly [had] trouble figuring [this] out, [since] there's a problem as soon as you [start asking questions like], "What are the actual numbers? How much younger is the right mirror? How much older is the left mirror? Where do you get the numbers for that?"

This is where that minor error I mentioned about the coordinate systems comes in. [It turns out that] if you make the choice that Einstein made, you only get paradoxes [when you attempt to answer such numerically precise questions]. And that's one of the reasons why I think he may have backed off from talking too much about this. [I suspect he had worked through the numbers enough to know something was amiss, so] he didn't feel comfortable with it.



[42:04] Does the internal asynchrony [of a small system moving through a much larger inertial frame] matter? Can [someone inside that moving system even detect their asymmetry from] inside the system?

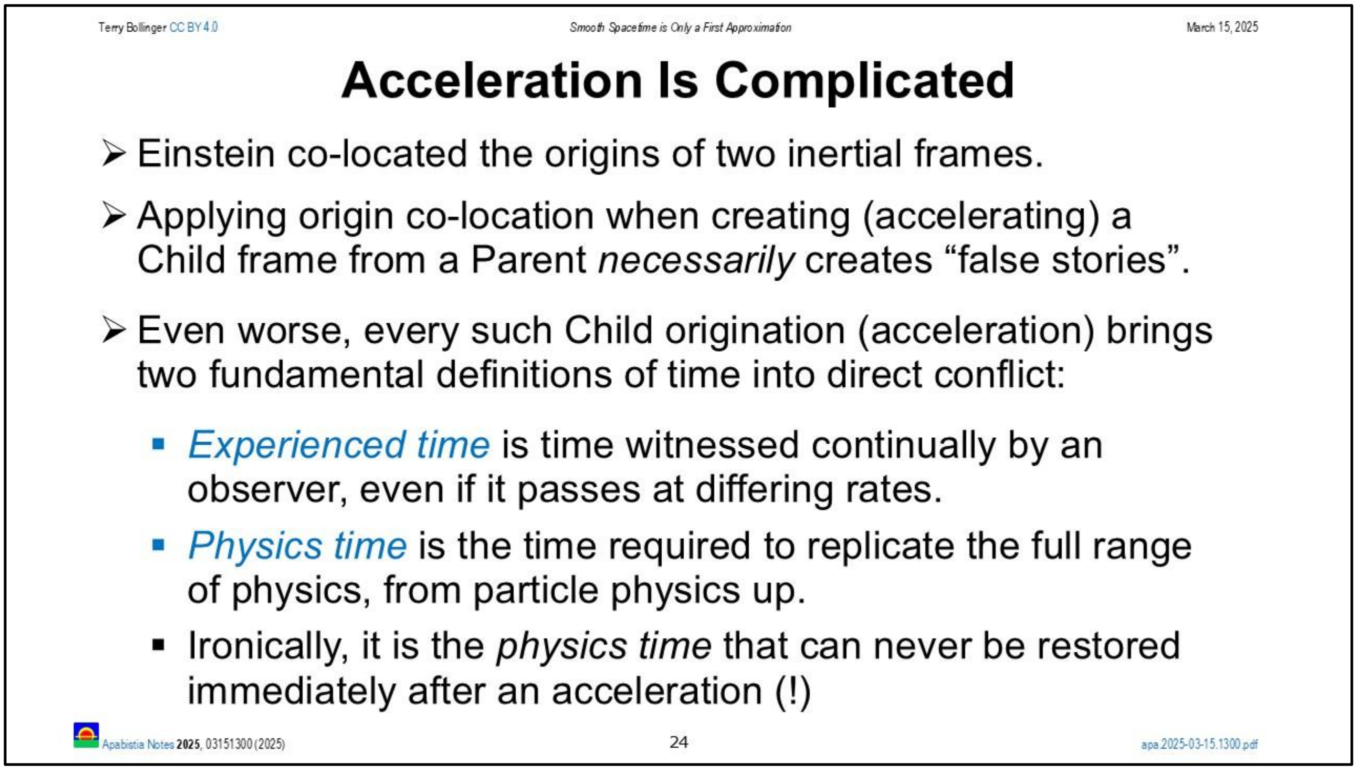
No, [they] absolutely cannot! This is where the symmetry of inertial frames is just *gorgeous*. Every inertial frame has a *perfect* view of physics — of *everything*. It all works the same! This is exactly right.

The trouble with relying *only* on that is [that] it forgets the fact that all systems originate from some *other* frame. There is a *history* involved with this, and if you simplify your math *too* much and say, "Eh… I don't *care* about that," you've got to be careful. In this case, the origins of these systems make a difference in terms of both their internal structure and how they behave to [observers] outside the system.

One particular example — and this is where I think people can get hosed [by using] too casual of an understanding of spacetime — is that if you accelerate to a high velocity and [thus create] your own new view of the universe, your view *does not extend or change the past* that you had prior to that acceleration.

[That is,] you don't suddenly have access to some past that didn't exist before, which can be an intuition [that adversely affects you interpretation] if you're not careful. You [may] think, "Oh, it's the *whole universe* I see [using my new coordinate system and its associated definition of history and causality], everything in a different way. *No!* You are still bound by exactly what you saw before, [including the causal history of your origination frame].

So, you want to be careful about the impact of *origination* on these different inertial frames. Poincaré symmetries are powerful, but they do *not* track that issue — and if your math is too simple to track the reality of what's going on, you [need to transition to] a more complicated mathematical system. …The [Poincaré] symmetries are beautiful, yes, [but] you can get really wrapped up in symmetries and [fail to] realize they're not tracking the actual history, information, and causality [of any system beyond the one created around you by acceleration from an earlier frame with its own causal history]. And if you're abandoning careful tracking of causality, you can have some problems.



[44:24] The point is [that] acceleration is complicated. If you think, "Oh, it's just the second derivative velocity!", or, "Oh, it's just a boost!" — no, it's *not!*

Acceleration actually is one of the *most interesting* features of physics. I could go on about this in terms of the quantum domain — my goodness, there are some interesting things that can happen in the quantum domain with acceleration.

But for this [talk] on relativistic [physics], what happens is [that] you can't collocate [the origin of the original frame's coordinate system with the origin of the new coordinate systems of any smaller systems created by acceleration of finite subsets of that original larger system].

[That is,] you can't do what Einstein described in 1907 [when he derived his original frame coordinate transformation equations] without creating false stories. [If you try to do it the way Einstein did,] you wind up [creating] a paradox about who's doing what, when, and you…create views of the past that *do not correspond* to any actual meaning. You set a clock back to a time and say, "Oh, yes, …this clock is [set to] one year in the past." [But] do you have access to one year in the past? "No, I don't. I just *set* the clock one year in the past." You get that kind of conflict with [Einstein's assumptions].

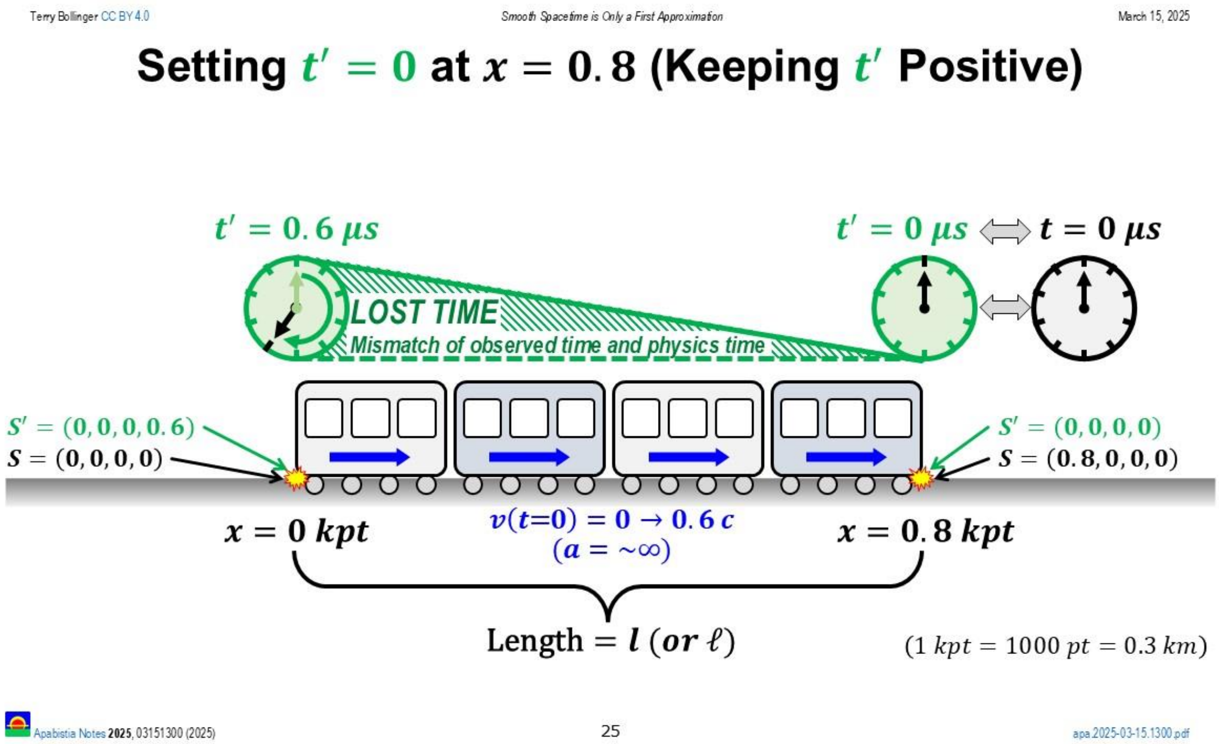
What I think is the most fascinating part of acceleration…is that you get a conflict on *two* fundamental definitions of time. And by "fundamental," I mean, you…can't get much deeper than these two.

The first one is *experienced time* — how much time actually elapsed while you [were] continuously observing it, and you *know* there was no gap. You might see a slowdown — that's fine; you can have slowdowns [or] speedups, that's fine — but you still see a *continuous* elapse of time. So, you have an experienced time, and it turns out [that] when you accelerate a system, [the irony is that how you label this continuous passage of experienced time] has to break — something [in your labeling of experienced time] has to break, [such as by introducing a gap (*lost time*) in how you label experienced time — to reconcile experienced time with the second form of fundamental time.] …

The other [fundamental time in accelerated systems] … is *physics time*, and this [one] is even more intriguing. When you accelerate a system, you *break* physics time, for a while, within that system. It takes a while for the system to return to [the] state … Einstein described [as necessary] to measure *any* aspect of physics, and [thus verify] that all the physics [in the newly accelerated system] is *exactly* the same [as the physic in the larger system from which you created the new, smaller system]. It takes *time* to get [the smaller system] back to that state [of identical physics]. Now think about that: You *don't* instantly get measurable classical physics when you accelerate a system, especially if the system is large. It takes *time* before you can return to full analytic capability, with a full definition of space and time again [in force].

That is deep! When you're talking about classical physics time, you're talking about *quantum physics*, [since that is always embedded in classical time]. You're talking about the *definition* of a point particle. You're talking about some really profound aspects of what we think of as "just standard physics" [that] turn out to be *shredded*, for a while, after you do an acceleration, [at least] in terms of being [experimentally] measurable. You can always do an abstraction, but let's stick to what's actually measurable. It takes time to recover that.

This is saying something important. This is an issue I'm continuing to explore, but it says something important about the impact of acceleration on that system, and on the systems around it. When I say it's interesting, for instance, I would bet you this is related to the whole idea of quantum collapse. When you have this conflict in [the classical observer definitions of] time with the [time as defined at the] micro [or quantum] scale — [with] what's happening [dynamically] at the micro scale — this [conflict in the large-scale fundamental time definitions] is going to play havoc with some of your definitions of time at [the microscopic or quantum] level.



[48:02] So, let’s [use this figure to] look at this “lost time” issue a little more carefully. As it turns out, [lost time] is *not* [the approach] Einstein [used],… [but I’ll get to that in the next slide.]

[This slide is messy — too many numbers on it — but its central message is easy enough: Every time you accelerate a large object, you must *reset every clock* in that object — and, somewhat counterintuitively, begin that clock resetting process from the *front* of the object, not the back.

Say what?

I would wager that every special relativity you’ve seen before this one showed you what a Lorentz contracted object looks like *after* the acceleration process finished. There’s nothing wrong with that, and such already-stabilized accelerated states delightfully demonstrate the beauty of the Poincaré and Lorentz symmetries.

However, did you ever stop to think whether there might be a few sneaky little “gotchas!” along the way to that pretty final state? For example, did you ever stop to think that when you change the definitions of space and time for an accelerated object, the initial internal locations of its components when it was at rest state cannot possibly be correct according to the new definitions? This means that to get the object to work correctly *after* acceleration, you must *physically alter* the locations of its components in space and time to make them compatible with the potentially very different post-acceleration definitions of space and time.

Don’t feel too bad if you never considered the need to move stuff in an object after acceleration, since no less a figure than Einstein also missed it — or, to be precise, Einstein clearly *worried* about the issue without ever coming up with a satisfactory solution. His concern showed up in the footnote to his coordinate transformation equations in which he explicitly stated that his derivation was correct *only* if such transformations were *not* to be the case. The possibility of object transformation worried him enough that he added that qualifier. He was correct to be concerned.

I’ve already added one such shuffling of train parts to this figure by showing the train as *already* Lorentz compressed before it accelerates. You can do that because the space and time transformations needed to move parts into new positions are separable. We don’t normally notice this separability because any form of solid or liquid matter will object strenuously to being compressed *prior* to acceleration. However, for entities such as diffuse gases and radio-linked satellites in space where empty space separates the individual components, such prior repositioning is not only possible but *required*. If you don't do it, the post-acceleration object ends up distorted in its new definitions of space and time. Lorentz compression is not magic: It's an *entirely real* compression that someone must perform at some point in the acceleration process to make objects compatible with new definitions of space and time.

(Incidentally, one distressing — but also unavoidable — consequence of recognizing the need to track internal object reconfigurations during acceleration is the need to abandon Minkowski's mixed-signature pseudo-Euclidean 4D spacetime due to the impossibility of tracking causality properly in Minkowski's oversimplified model. To replace it, one needs to use a hierarchy of fully Euclidean 4D center-of-momentum (COM) frames, which are also called zero-momentum frames. More specifically, you need to replace every use of mixed-signature Minkowski spacetime with use of the smallest Euclidean 4D COM frame that encompasses *all* of the material objects involved. Incoming energies — light, for example — can generally be rescaled to match the new frame, so the main focus is to ensure that the sum of all fermionic matter involved in the interactions forms a zero-momentum frame. This Euclidean 4D Minimum-Encompassing COM (MECOM) then serves as the canonical frame for all causal analysis and prediction within the frame. Moving objects inside the MECOM become Minkowski trapezoidal distortions characterized by broken time lines (lost time) and asynchronous internal time. MECOMs can vary enormously in scale, from two interacting particles (e.g., a hydrogen atom) to cosmic scales, provided only that they encompass all participating matter and (potentially rescaled) energies. It is this flexible scaling that allows MECOMs to replace Minkowski space representations, though (fortunately) without the Minkowski disconnect to experimental time.

Despite its long use and popularity, Minkowski's concept of mixed-signature spaces is, unfortunately, math noise created by focusing on only too small and simple of a subset of the actual physics problem. The resulting incompatibility with Einstein's far more precise clock-and-ruler analyses explains why Einstein initially rebelled against Minkowski's needlessly cryptic model. Unfortunately, Einstein did a complete flip on this issue after Minkowski's untimely early death in 1909 from appendicitis. Around 1912, Einstein abandoned his methods and switched to Minkowski's spacetime, likely in a case of survivor's guilt over his earlier arguments with Minkowski.)

Getting back to the figure: Notice that my figure invokes *instant acceleration* of the entire train to $v = 0.6\,c$! Just as in my earlier example of impossible pre-Lorentz-compression of intransigent atoms, it is, of course, physically impossible to accelerate a real train this quickly.

However, consider this: Effectively instantaneous accelerations ($a = \sim\infty$) of individual particles to velocities near lightspeed are one of the commonest physics phenomena in the universe. We call them radioactive decays and emissions, which routinely accelerate all of the constituents of ordinary matter — electrons, protons, and neutrons — and even small atomic nuclei (alpha particles, which are helium nuclei) to velocities very close to lightspeed, and manage to accomplish these accelerations within immeasurably short times.

Thus, while no one can instantly accelerate a real train to $0.6\,c$, one *can* postulate instantly accelerating particles such as muons to form the outline of a train that accelerates to $0.6\,c$ within an immeasurably short time. Since muons decay at a fixed rate, they also serve as the clocks. Since the physics that applies to the muons also applies to the train in which they could have been embedded, the behaviors of such muons end up showing how an instantly accelerated train would behave.

This equivalence of the implied physics is why I dared to use "instantaneous" train accelerations in my figure. Trains are easier to visualize than muons, and make it easier to understand the associated transformations.

The analytical advantage of instantaneous acceleration is that it puts the focus onto how causality works during frame transitions, rather than on how to calculate the sum of many small examples of such transitions without explaining how they work. Most special relativity acceleration models focus on the calculus problem of how to integrate many small boosts into one large overall boost. Unfortunately, such an approach — which Minkowski also proposed — gives no insights on how space and time change with each *infinitesimal* step. This approach unfortunately left the entirely false impression that tracking how time works when changing inertial frames is all about using calculus to integrate slow accelerations. Not only is this incorrect, but it obfuscates the deeper nature o the time problem instead of solving it. Making the leap to *one* extremely rapid acceleration forces recognition of issues such as discontinuous and asynchronous internal time during acceleration.

I've already addressed the Lorentz compression example of having to *move* components to make them compatible with post-acceleration definitions of space and time. However, there is also a time relocation problem, and that turns out to be tougher to solve in a satisfactory fashion. The problem is to meet the time slope recommendations of α for the new frame, you must also move internal components in *time*. That sounds okay until you consider that moving a clock in time makes no sense: You cannot "move" any object to a specific point in the past or the future. All you can do is *reset* the clock to show a *time* in the past or future. Doing that feels like a cheat since if you reset a clock into the future, you create a "lost time" gap in your time accounting. Resetting your clock into the past is even worse, since in that case you imply a history — a sequence of causal events — that you know never happened.

In slide 25 figure I used the lost-time method for resetting clocks. The idea is to keep the clock at the right (front) of the train the same as before acceleration, and thus initially matches the $t = 0$ setting of any embankment clock at the same location. The odd part is that if you make the embankment and train clocks match on the front end of the train, you have to reset clocks towards the rear to values increasingly far into the future. There is no elapse of time when doing these resets, and such resets are no different from the ones folks do for Daylight Savings Time. The only difference in the case of acceleration is that if you *don't* make these seemingly arbitrary changes to clocks that seem no different from the ones at the front of the train, your time definition inside the train goes haywire.]

[Alternatively, I could have]…set [embankment and train time] to zero at the *left* [(back end)] of the train. [But that] is not what [I did for this slide; I'll cover that case in the next slide]. This [figure instead]…says, "Let's do it a little differently because [resetting clocks to *negative* times] doesn't make sense [physically]." So, [I instead] put the [shared] zero [time] settings, [$t = 0$ and $t' = 0$,] at the *right* [(front end)] of the train. [Why on the right?] Because you have a *negative* time gradient — a negative α. [This means you need to move] to the *left*,…to *add* time to your clocks [and avoid negative times.]

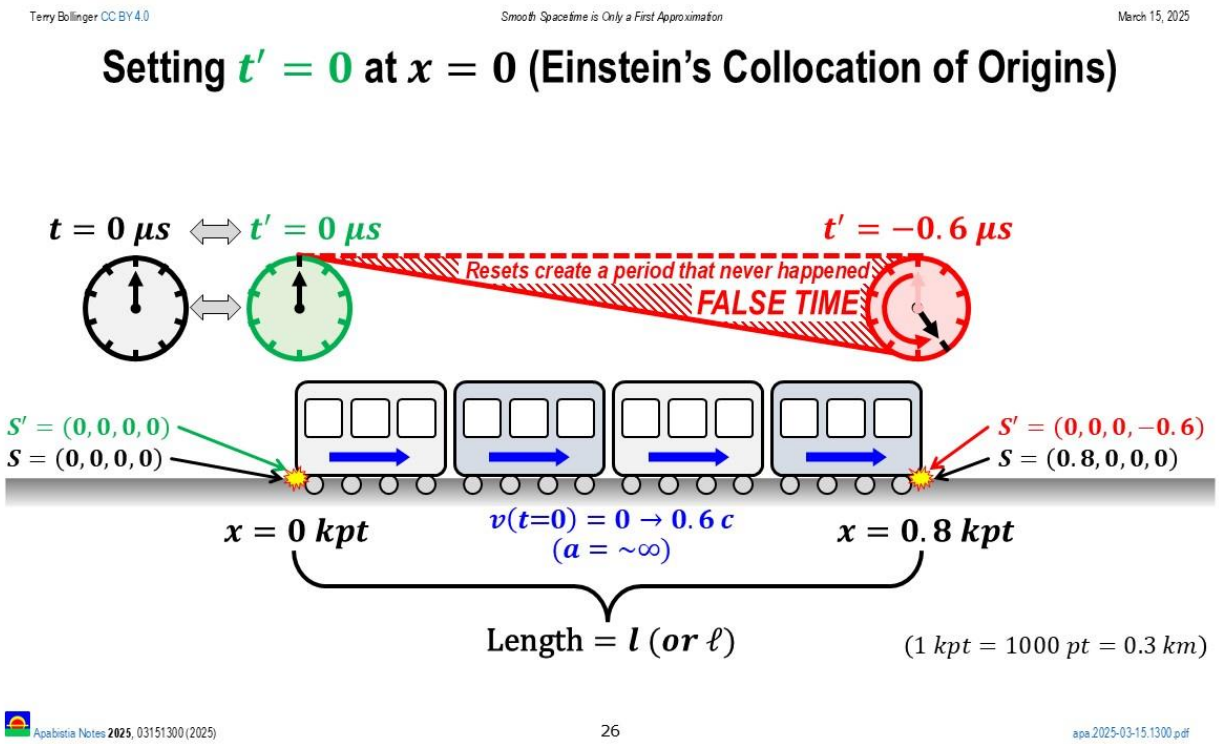
[However, if you are someone on the *left* end of the train,] this is distressing because [you will say,] "I didn't *experience* that time.…I didn't see any time go by! I just *reset my clock*."

[Again, it's] exactly like Daylight Savings Time: "spring forward," [that is], set [your clock] an hour ahead.…You can *do* it, but it's unsatisfying because [people at different locations along the length of the train must reset their clocks differently.] You [cannot help but] think, "How did that happen?…Why did *I* have to [reset my clock ahead when the person at the front of the train did nothing to their clock?"]

[The answer is that] until you do that,…you cannot come up with a self-consistent [physics] definition of either time or space [across the length of the train]. Your new inertial frame is at a different angle in space and time from what it started, and you have to do [reset clocks differently along the length of the train] to recover the idea of classical precision down to the point-particle level.…So, it's not [a process] you [can] skip over. You have you have to do it.

If you have a material body that's being accelerated, all [of] this gets taken care of for you at the atomic level you know because the atoms jostle themselves and…figure it out pretty much on their own.

If you're doing it with satellites, [however,] no such luck applies. You have to do an *explicit* resetting of [clocks along the length].

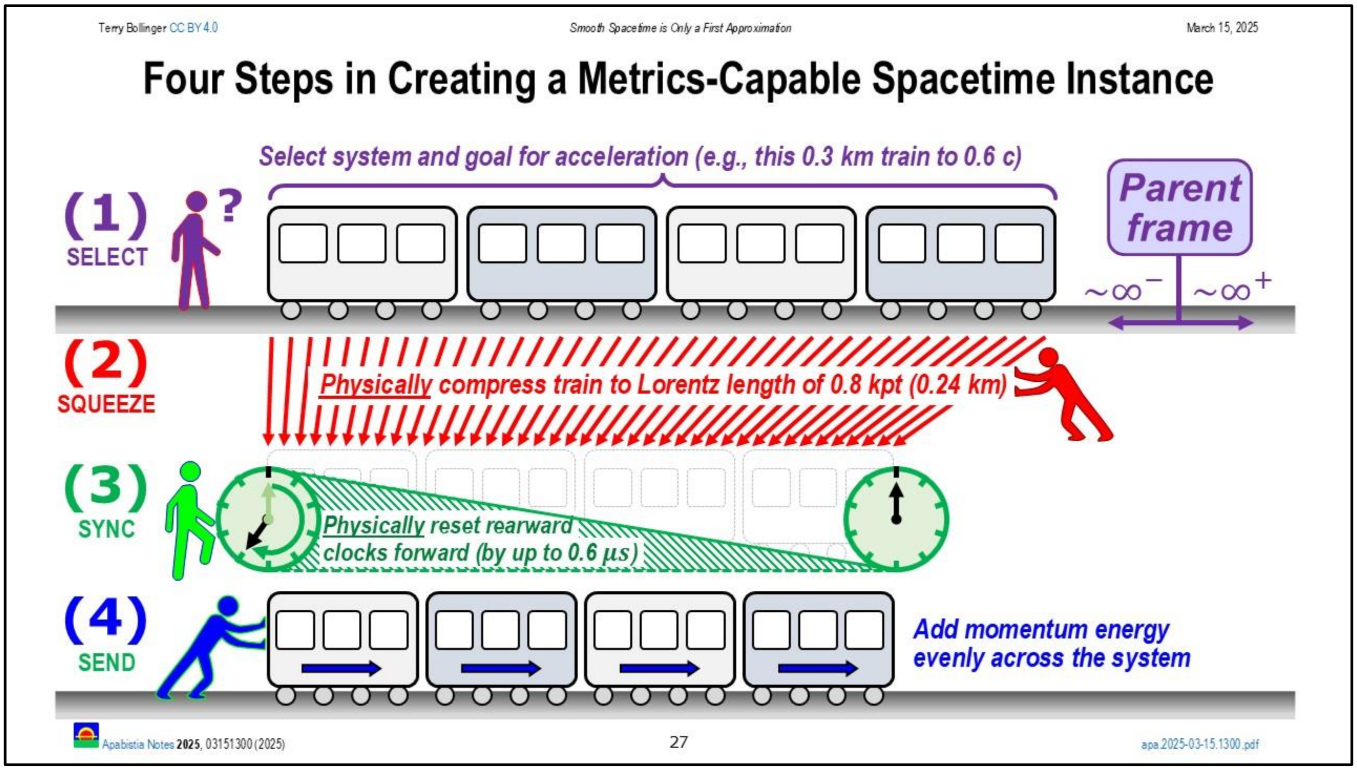


[50:06] [This figure shows] the alternative, [which is to place the matching zero times on the left.] This [is where] we get back to what Einstein proposed, and why I say that this seemingly completely minor mathematically obvious thing of saying, "We'll just [make] the coordinate [origins] identical for the two systems," does *not work* when you accelerate a system from [one frame into] another frame. You have a *history* here, and what this does is [force you] to reset the time clock *backward* in time [into a history that does not exist]. This is where you get your issue of false time, and you don't want to do this.

The other the other alternative [of placing the matching time on the right] is better. It's *annoying*, but…at least it does not create any false time paradoxes, [whereas] this one does. It says that I had 0.6 microseconds of time that I *didn't really have*.

(And, by the way, the units here are kilo-photon-feet. So, same idea [as before, just scaled up a thousand times.] It's 0.3 kilometers instead of 0.3 meters.)

So, this is interesting. Who would have thought — it's not obvious — that such a small choice would have such an odd impact on how you measure time these systems?



[51:12] [In this figure,] we get into a full model of, "What is acceleration, *really*?" So, again, forget "boost" for a while. Instead, look at this in terms of — and you can slice this and dice this in different ways — *four* different steps.

First, you have to *Select*. (I did a little alliteration: *Select*, *Squeeze*, *Synch*, and *Send*. It just makes it a little more memorable, but also it's pretty apt.)

[For *Select*], you have to select an *actual length* of an object. You have to say, "*This* is the system I'm accelerating." …I just can't say that [my new inertial frame] goes beyond [the boundaries of] that [system.] I have to say, "*No*, *these* are the pieces of matter that I'm going to accelerate," because I can *only define* my new spacetime [in an experimentally meaningful way by] using [some fully compatible set of clocks and rulers contained within that] set of matter."

The next… step, [*Squeeze*,] …is counterintuitive. You'll see all sorts of complicated explanations about why, if you have a rocket going at [nearly] the speed of light through a barn, and you shut the barn door here, and shut the barn… there, [a rocket longer than the barn nonetheless can fit between the closed barn doors. Such explanations can] get very complicated!

The simple truth is [that] the reason [the rocket] gets through the [closed doors of a] barn [whose length is shorter than the rest length of the rocket] is because you *squeezed* [the rocket] before you ever sent it [into the barn]. It *really is shorter!* This is not some mathematical abstraction — you had to *squeeze* that sucker! So, it's smaller… than it was, and goes through the barn fine.

[Recognizing the need for a *Squeeze* step thus provides] a refreshingly *blunt* way of describing some of these paradoxes. And yet, it's not that the other ways of [describing] it are incorrect — they're actually quite accurate. It's just [that] there's a simpler way to think of it, [which is to] recognize that this is an *actual physical step* of *squeezing* the system together.

When you're accelerating in a car? No problem! [That's] because the [length] of the car is gigantic compared to the amount of length contraction you use. When you do satellites? Not so easy!

The third step, [*Synch*,] is the one that, as far as I can tell, Einstein [missed. Though, to be more accurate,] I don't *think* he [really] missed it. I think he just kind of felt uncomfortable with it because of that decision he had made earlier [in 1907 to place the shared-time point of the train [and the embankment] at the back (left end) of the train. As a result of that choice,] he couldn't see how to [avoid] getting those negative times in the front.

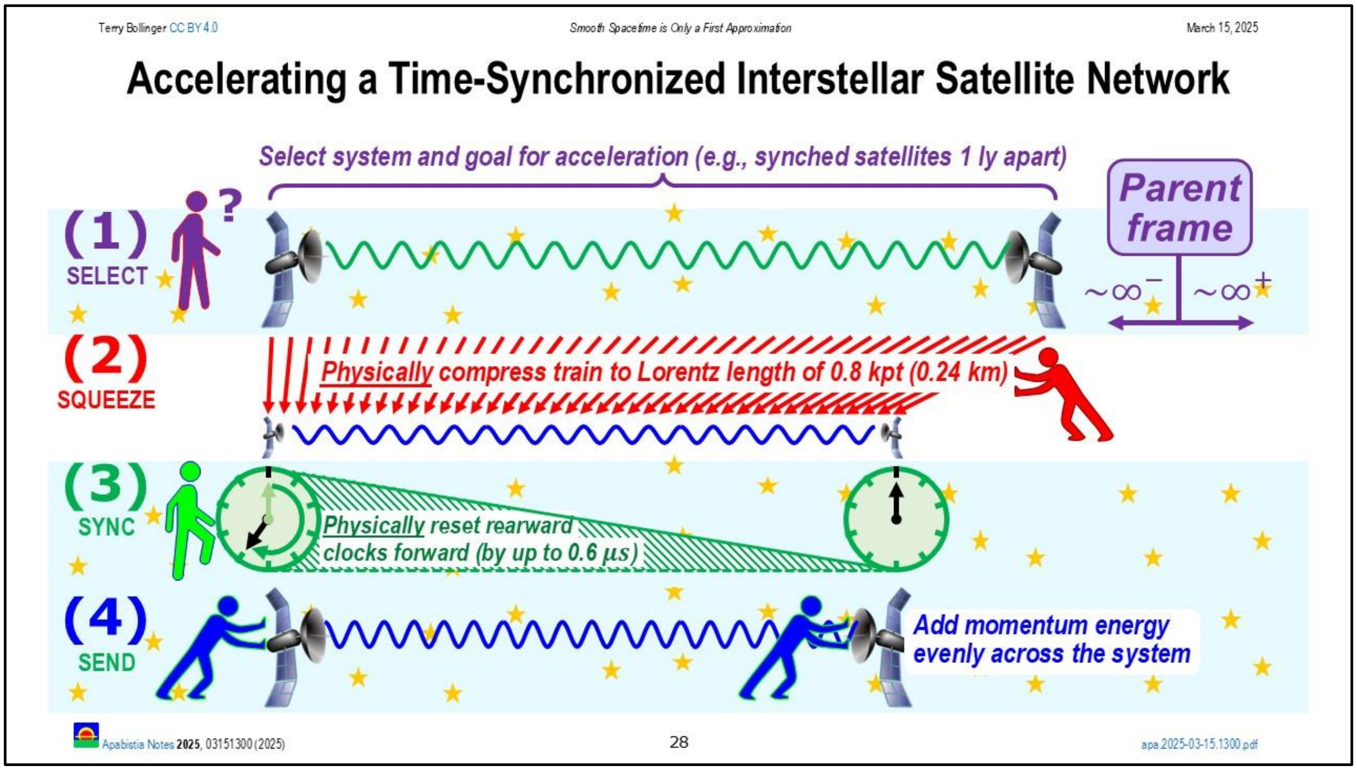
So, instead [what I show in this figure of [that puts the shared time point at the *front* (right) of the train, Einstein] left it at the *back* of the train and kind of said, "Hmm… *something* happens." So, it's really fascinating how he did *not* address that particular issue.

To get [a shared time-point] that is, at least, not paradoxical, you have to add a parameter. You [must add in] that previously selected length, set the $t' = 0$ at the *front* [(right end) of the train], and reset the [train] clocks behind [that front clock] so you get an [increasing positive] time delta as viewed from the [embankment].

And then, you finally [arrive at the fourth step, *Send*, where you] add *momentum* everywhere. You can have things like, "Every car has its own rocket," if you want to do something like that. Again, with satellites that [idea of individual accelerations of components] becomes more realistic.

These steps can be mixed and matched. You can, for instance, reset the clocks first with a slightly different sequence [and] compress second. So, there's some variability in how you do that. You can, [for example,] get more complicated schemes so [that] the compression is more efficient. There are a *lot* of parameters that you can play with, but this sequence captures the major differences and the *physical* steps that you have to do to accelerate a system [in a fashion that] creates a *self-consistent* definition of spacetime within that object: [a definition] that will see the same *quantum physics*, the same *particle physics*, the same *everything*. [To get that,] you *have* to go through these steps.

And that is *remarkable*! [It's astonishing to] have to go through this much of a physical procedure to get to the point of having classical physics covered and measurable. You can always say, "Well [all of that physics is] there by default [regardless of whether a material system occupies that new definition of spacetime]." But if you want to talk about *measurable* physics, as Einstein did when he gave these examples with the clocks, you have to go through this.



[55:08] Here's the [same] example for the Interstellar Satellite Network!

I like this one because it's the same as the previous figure, but [helps] point out there are very real [time and space] issues in how you [create a large working physics system after a correspondingly large acceleration operation]. You can't just *assume* that a satellite's going to suddenly magically [move] over 0.2 *light years*. *That's* not going to happen! You have to *send* it — *accelerate* the satellite on the right — send it in farther [to the left] — and [then] *compress* the whole system before you can get [the full satellite system] working [properly again].

Oh, and you're going to have *synchronization* issues! [It] could take you a full *year* to resynchronize. [Do] you see how this is getting messy?

After you do that — *and* after you've reset the clocks, substantially this time, with a *huge* jump in the [clock time settings of the] satellite on the left — *after* you do all that, and add your momentum — and again, you can mix and match these [individual steps], you can do them in different orders — *after* you do all that, you *finally* recover physics: *Standard* physics, *particle* physics, *quantum* physics, and *field* theory.

Field theory? Isn't *that* interesting! Field theory doesn't *work* until you *recover* this [set of experimentally meaningful definitions of space and time for use with actual, material instruments. That] says something [very interesting] about field theory's relationship to matter.…

So, [the satellite network shows] that when [the topic is] special relativity, [you need to] talk about a [lot more than a] "boost." There's a lot more going on, and the steps *do* make a difference.

But Terry! Lorentz Contraction is Symmetric!

- Correct statement:

  Length contraction is symmetric only for lengths passing through your *local* definition of spacetime.

- Lengths forward of your region *shorten* (multiply) by the inverse relativistic Doppler factor: $1/R = \sqrt{(c-v)/(c+v)}$
- Lengths behind your region *stretch* (multiply) by the relativistic Doppler factor: $R = \sqrt{(c+v)/(c-v)}$
- Lengths passing through your region divide by the *average* of the two: $\big((1/R) + R\big)/2 = 1/\sqrt{1 - v^2/c^2} = \gamma$

[56:44] Now, let's get back to the other issue. I love this one! "*Terry*, Lorentz contraction is *symmetric*! You *know* it's symmetric!"

And I *do*, and I agree *completely*! Not only do I agree with it, I think, if anything, I'm even more enthusiastic about it. If you have an inertial system that you have accelerated, I say that the physics is *absolutely* identical. Don't tell me that it's going to reach some upper limit! No, you can you can accelerate to 99.999999% of the speed of light and it doesn't matter one lick! You're going to get *exactly* the same physics in that system after you've gone through those steps I mentioned — which are *hard* if it's a big object — but if it's a small object, like a proton, you can certainly do it down at that level. So, it all works, and those symmetries say that Lorentz contraction is *symmetric*.

[The catch in Lorentz contraction is *where* the symmetry works. While the symmetry is perfect at the physics instrumentation and testing level, the size difference of the regions which such instruments can access a single, shared definition of space and time can literally be astronomical. If someone accelerates a well-defined system, the same-physics domain for the *unaccelerated* or Parent system can be as large as the cosmic microwave background of the entire universe. Meanwhile, the same-physics scale for the *accelerated* system ranges from microscopic (accelerated particles), through classical scales (cars and spaceships in smooth motion), and up to entire stellar systems condensed out of near-light-speed large quasar jets. Establishment of accelerated same-physics domains beyond stellar-system scales becomes difficult due to the increasingly vast times need to resynchronize the matter in such systems to share a single set of space and time coordinates.]

You've often heard — or maybe you've thought — that if you are in a spaceship, and you look at the outside universe, it's going to look flat as a pancake. Did you know that's *not* true? It's *absolutely* not true. But people talk about that on the assumption that the Lorentz contraction is fully symmetric, and they *assume* that it's true.

What you actually get is a very interesting phenomenon in which the *forward* appearance — and of course, there's a there's a whole equation to go from forward to backward — but the *forward* direction is *compressed*, is *contracted* — *not* by the Lorentz Factor, but by this relativistic Doppler Factor: One over... [the square root of this] very simple expression [of c plus v over c minus v]. ...Object lengths *behind* [your ship] are multiplied — they're *stretched* —

and, if you think about it, is that really that unreasonable? Light is *chasing you* from behind, and it's being *jammed into you* from the front — and light is a measure of distance. So, why should it be a surprise that things in front are compressed?

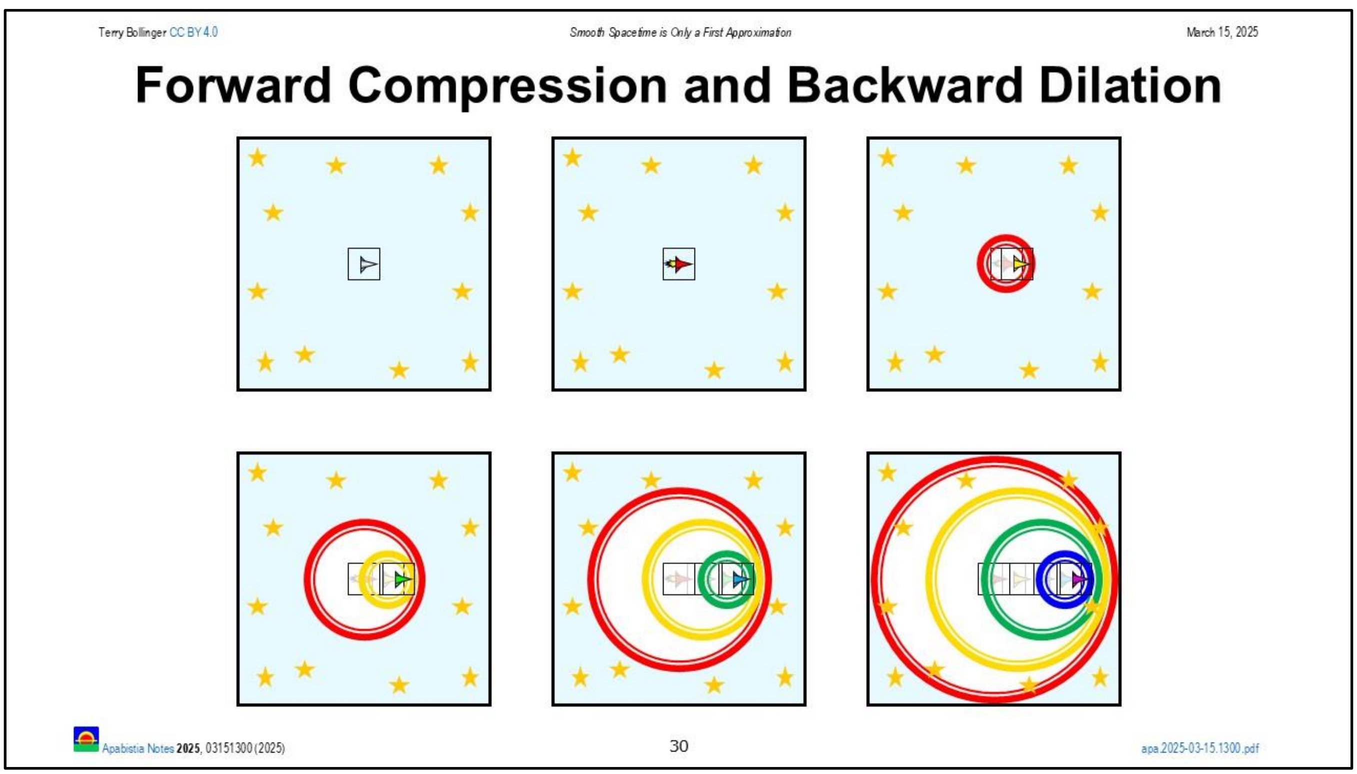
So, that's what you actually see. You see something much more complicated than what you had before [with the simple Lorentz compression assumption.]

Now, I said Lorentz contraction is symmetric. Where is it symmetric? *Inside* your spaceship, *only*. When you have an object such as a particle that passes *through* your spaceship — let's say you have a muon that's decaying — as long as that muon is *inside* the domain of your spaceship, you *will* see it time dilated, *tremendously*. You'll see it going right through, and [it will behave] *exactly* as you would expect, because your physics *rules* inside the spaceship. Your physics, and your physics *only*, *rules* for the set of matter that is defined by your spaceship and you. And you will see the time dilation you expected.

And you will say, "Well, then, how is that *possible*? That muon can't *possibly* have lasted the entire duration of your trip!" Well, that's because [you must] go back to what I just said: In the *forward* direction [muons] actually decay *faster*. In the *backward* direction, [muons] actually decay *slower*.

([Incidentally, just to point this out:] The [slowdown factor in the backward direction is the relativistic Doppler factor. That and the Lorentz factor] approach each other [in magnitude as the velocity gets closer to *c*,] so Lorentz factor becomes almost the same [as the relativistic Doppler factor] after a certain point.)

So, [the muons passing through your ship] go Slower, but it's *only* within the domain of your ship that you see the Lorentz contraction that you expect. [It's] a fascinating little effect.



[1:00:32] Another way of looking at these same [special relativity] issues [is expanding spheres (or circles) of influence.]

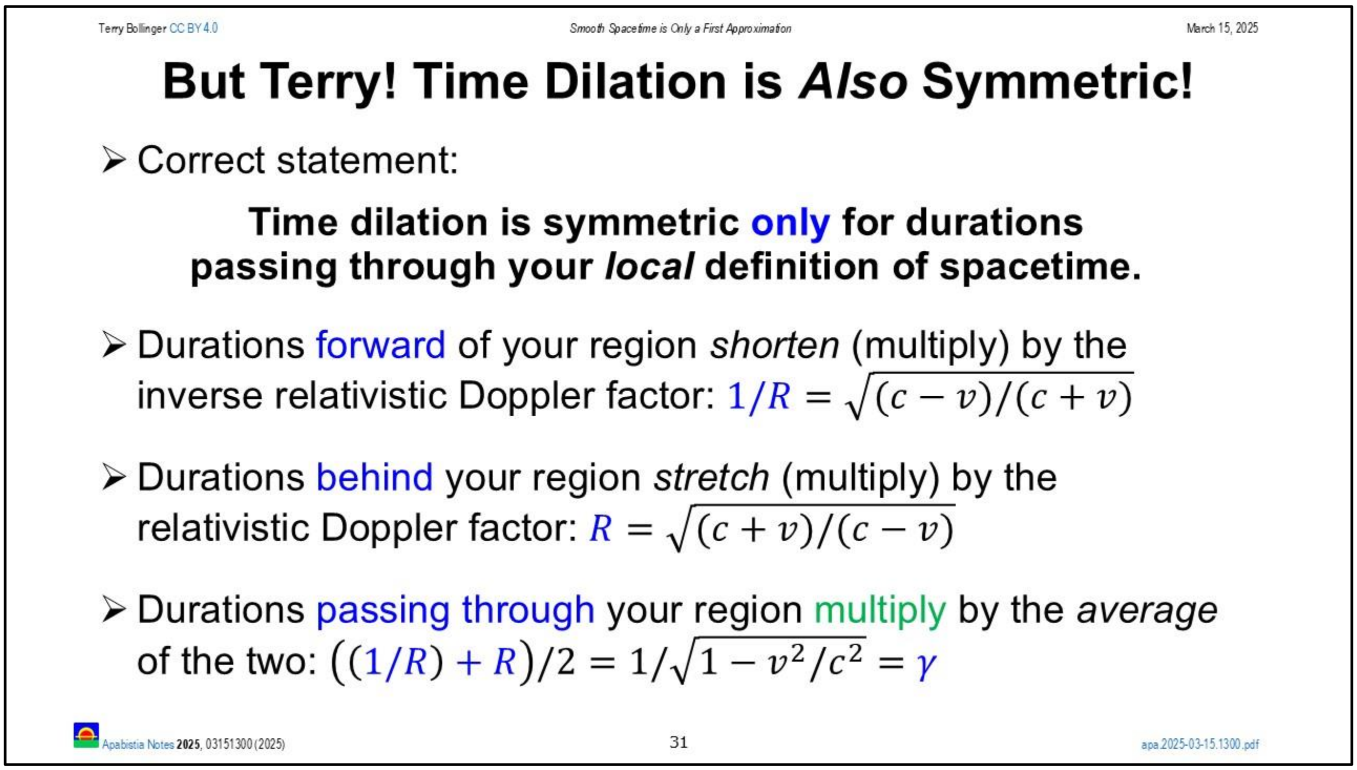
(An important quantum sidenote: I [also] use this [expanding circles model] for quantum mechanics, [specifically] when people talk about the *instantaneous* impact of entanglement. There's no such thing! The only thing you see is a radiating circle of influence where you *could* have touched something the outside. And until that circle touches a distant spot, it doesn't *matter* if the particle is entangled there or not. *That* is the only time in which that point sees a change. So, entanglement is not what people think it is. Are there strange correlations? You bet! But you have this speed-of-light circle that you have to respect. So, that's quantum side this side.)

[Getting back to] this side [of special relativity in these expanding cones of influence], I'm just pointing out that, *there* [in the figure] is your compression effect, right there: It's like a cone leaning to the right.

It is not *quite* a shock wave. A shock wave is when you go *beyond* that. I've never seen a really good term for these sub-shock waves [that are] *almost* shock waves, but not quite.

But whatever you might call it, just looks like a cone that leans closer and closer, and in the front gets more and more compressed. You get the gradients until you get to the rear side where you get the stretching.

So, this is another way of looking at that same issue: backward and forward compression.



[1:01:54] "But Terry! Time dilation is *also* symmetric! Isn't that a problem?"

Well, yes. [But] the same [regional-by-acceleration-history asymmetry of where the Poincaré symmetries apply also affects time. For example,] anytime you hear about blue-shift, here's a simple thought — [well,] maybe it's not that simple, because it [certainly] took me a long time to figure it out — [but the thought is this:]

A light wave is a clock. If it's circularly polarized, it looks *exactly* like a clock. And when you have [a light wave that is] blue-shifted, it means the clock has been *sped up*.

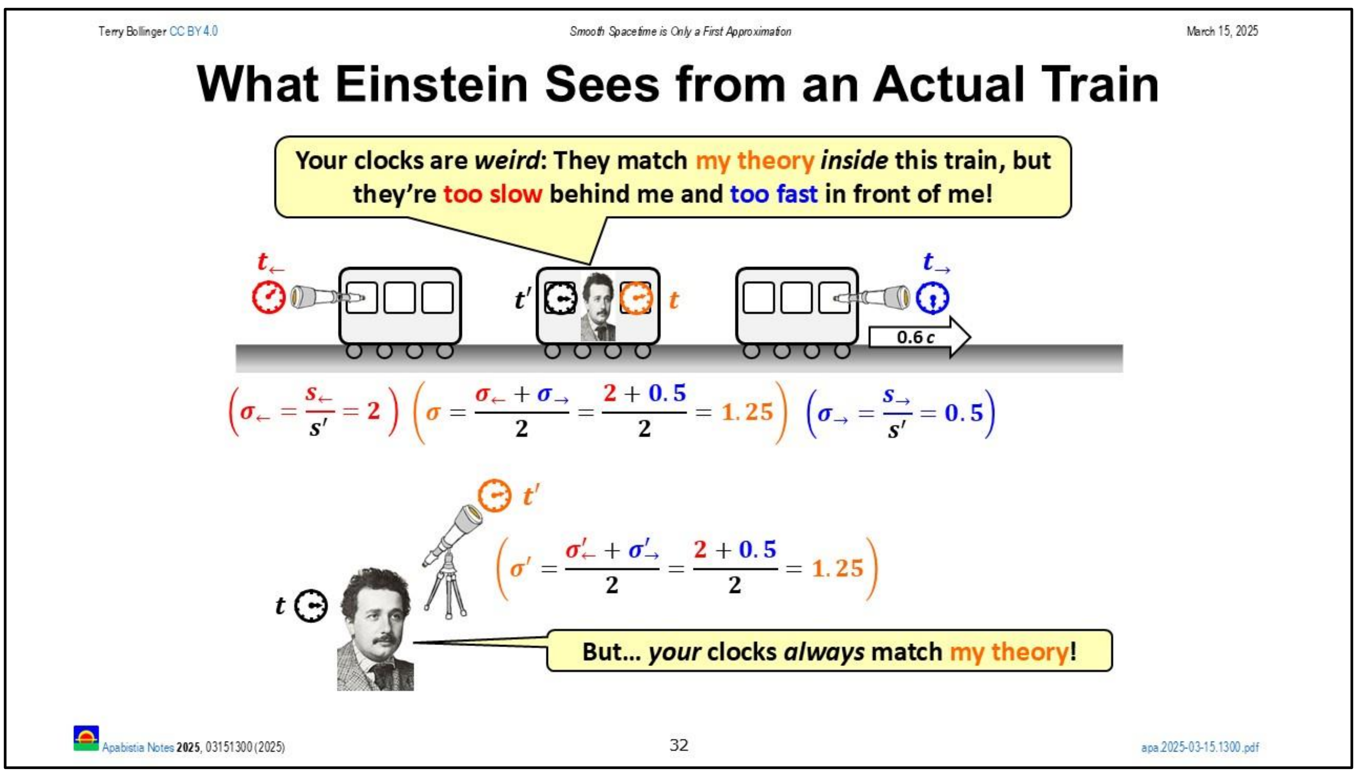
We talk about time dilation is if it's *only* time dilation, [that is, slowing time down]. That's *not* what you see from a spaceship! You see time *sped up*. (I don't know if what the opposite word of "dilation" is.) You get a speed-up in the forward direction.

Is it a real speedup? You *bet* it is, because if you blue-shift all the way to the Andromeda [galaxy] in your spaceship, [then] when you get to Andromeda [galaxy] you will find it is *exactly* the time the [sum of all those] blue shifts told you it [would be]. There is *nothing* hypothetical about it: It was a time *speedup* in that direction.

If you look in the *rear* direction, you get [the opposite effect: a] time slowdown. [The nature of that slowdown is] harder to judge because you're not actually making contact — [and] until you make contact, you have issues about what's going to happen when your reverse directions. But the speedup in the front direction? You bet [it's real]! You've encountered those light waves, they are little clocks running through space, [and] every time you hit one, that time is *gone*.

Another way of saying this [is that your spaceship] is running *slower* than the rest of the universe. So, again, it gets back to this thing [that] when you speed up your spaceship, [you immediately initiate] a *real*, *continual* time dilation relative to the gigantic frame [— the universe as a whole —] that did *not* accelerate. And [your local-to-you-only time dilation is] going on *all the time*.

Once again, [though,] objects passing *through* your [local spaceship] region, like a muon — [for example,] if you've got some spontaneous muons generated [just in front of your spaceship] — they're fine. As long as they were created soon enough to get *to* your spaceship, [then] *inside* of your spaceship, they will look time dilated.



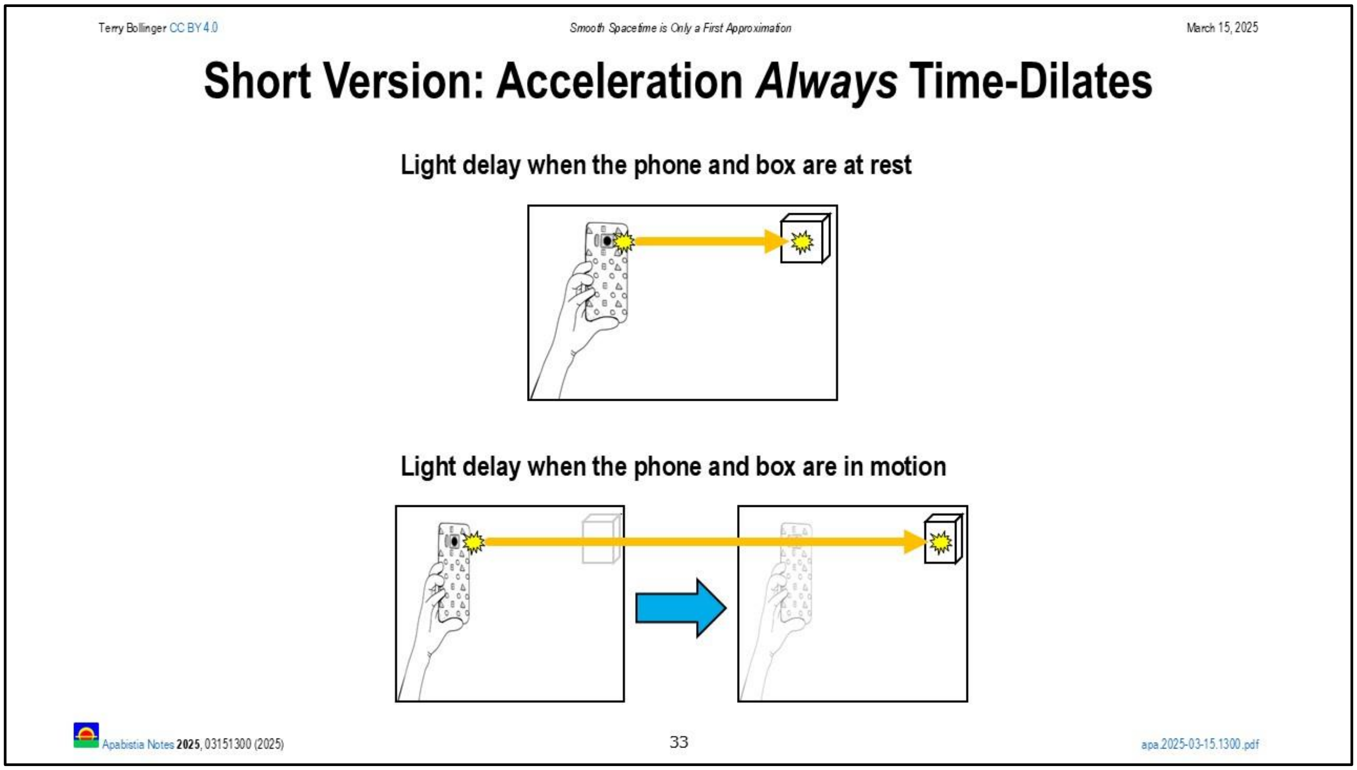
[1:03:55] Here's a little figure I made [as part of] a little article I had fun with. [It] talks about what Einstein would see if he actually [*rode* in] a machine that was traveling at close to the speed of light.

The Einstein on the *outside* would see exactly what he and Lorentz predicted, which [for this case of a velocity of 0.6 lightspeed] would be a time dilation of 1.25.

But the Einstein *inside* the [train] sees exactly what I was just talking about. He sees *blueshifted* clocks that are running faster in front, [and] *redshifted* clocks that are running slower behind.

And guess what? If you *average* the two, you get the Lorentz factor! The Lorentz factor is *not* fundamental. It is an *average* of the relativistic Doppler factor and its inverse. [This relationship] is not an accident because when [an object] is going through your particular train or ship, at that point, you're seeing *both* effects at the same time. You see [the relativistic Doppler factor affecting the object] in one direction, and [the inverse of that factor] in the other direction.

So, if you have a light clock going [through your ship or train], you'll see these two effects broken into two parts, and then averaged out to get [the Lorentz factor].

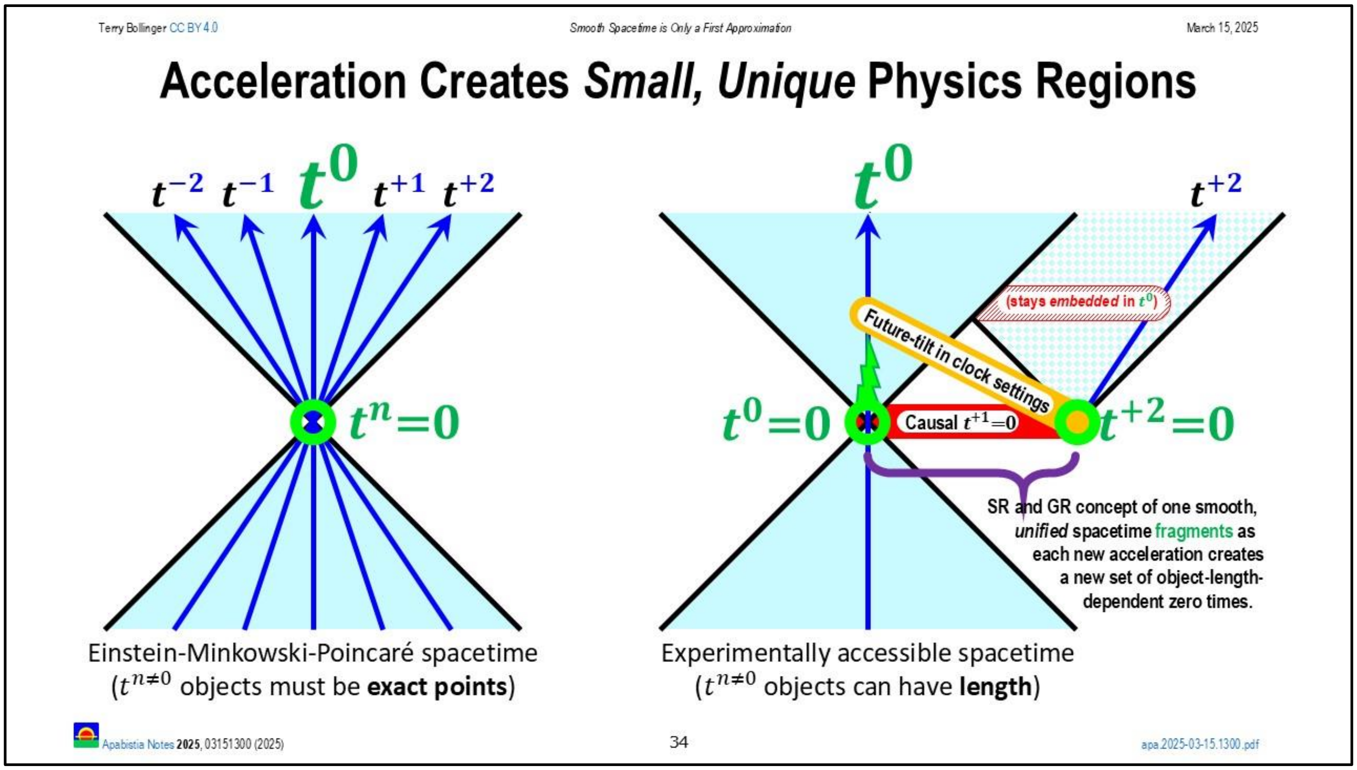


[1:05:10] A "simple" experiment — well, you can't *really* do this, unless you've got a *very fast car!* — but [it's a simple thought experiment that emphasizes how] we make time dilation too complicated.

It's a race!

If you're object is moving very fast, then it's going to take light a longer time to cross the path to get to the object in front. So, it doesn't matter whether [your object is] Lorentz compressed:… You've got your phone, you've got a little detector there, and it's just going to take longer [for the forward-directed light from your phone to reach the fast-fleeing detector].

That is the essence of why time dilation occurs. You've got a race in a forward direction against a speed of light. [This race is] continuous, it doesn't relent, and it starts the moment you accelerate [the object to] this high velocity. [Thus time dilation can] happen for conceptually very simple cases.

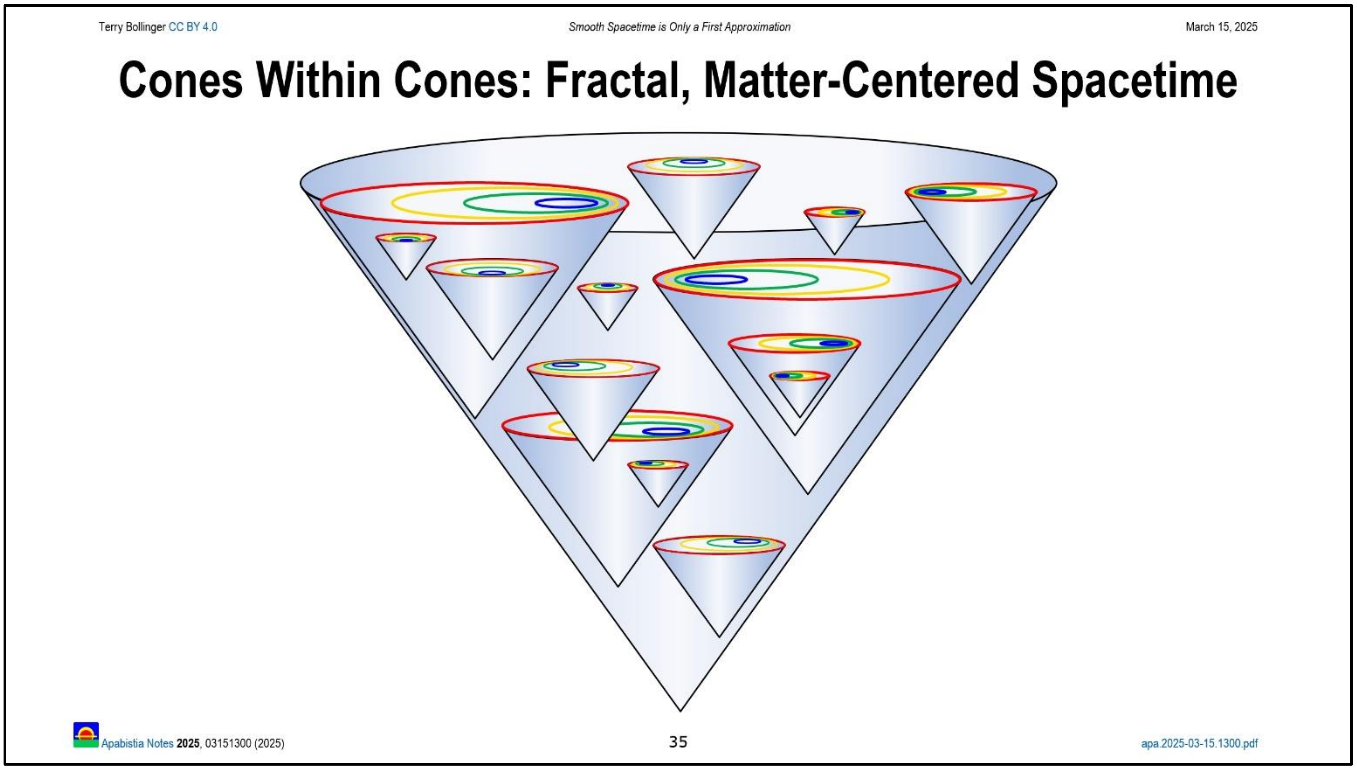


[1:06:08] Now,… [the reason I'm focusing on] acceleration, and [the idea] that spacetime is more complicated [than the shared-origin approach of Einstein suggests, is that] once you attach spacetime to units of matter that [are] not only are finite in size but take a little time to kind of *settle down* — they can take a *very* long time to settle down! — and start producing normal physics again, you *cannot define classical physics*.

[That is,] classical point-like metrical physics… — *including* quantum field theory, *including* quantum mechanics, *including* "you name it" — *all* those forms of physics as we measure them normally *don't emerge* until you get this consolidation of that small [set of experimentally usable metrical] units [that are fully aligned with their new inertial frame definition of space and time]. But once you've got [that set of fully aligned metrical units], [all forms of standard physics are] the same.

So, that necessarily breaks up the idea of smooth spacetime — Einstein's idea on the left [side of this figure], that everything could have a *shared* origin — kind of breaks down. This tilting process [on the right is] where you wind up things having a different definition [of space and time].

I'm kind of so-so on this [diagram because] it's too complicated.



[1:07:17] This [figure in Slide 35] actually gives the idea better. You have a cone — in fact, if you think back to [Slide 30] where you have cones moving…inside of other cones, that's kind of what this [Slide 35 figure] is. You're saying that…each of these smaller cones is in motion inside of [a] larger cone. [The smaller cones] *never get outside* that [larger] cone. They're always *bound* by that [larger] cone.

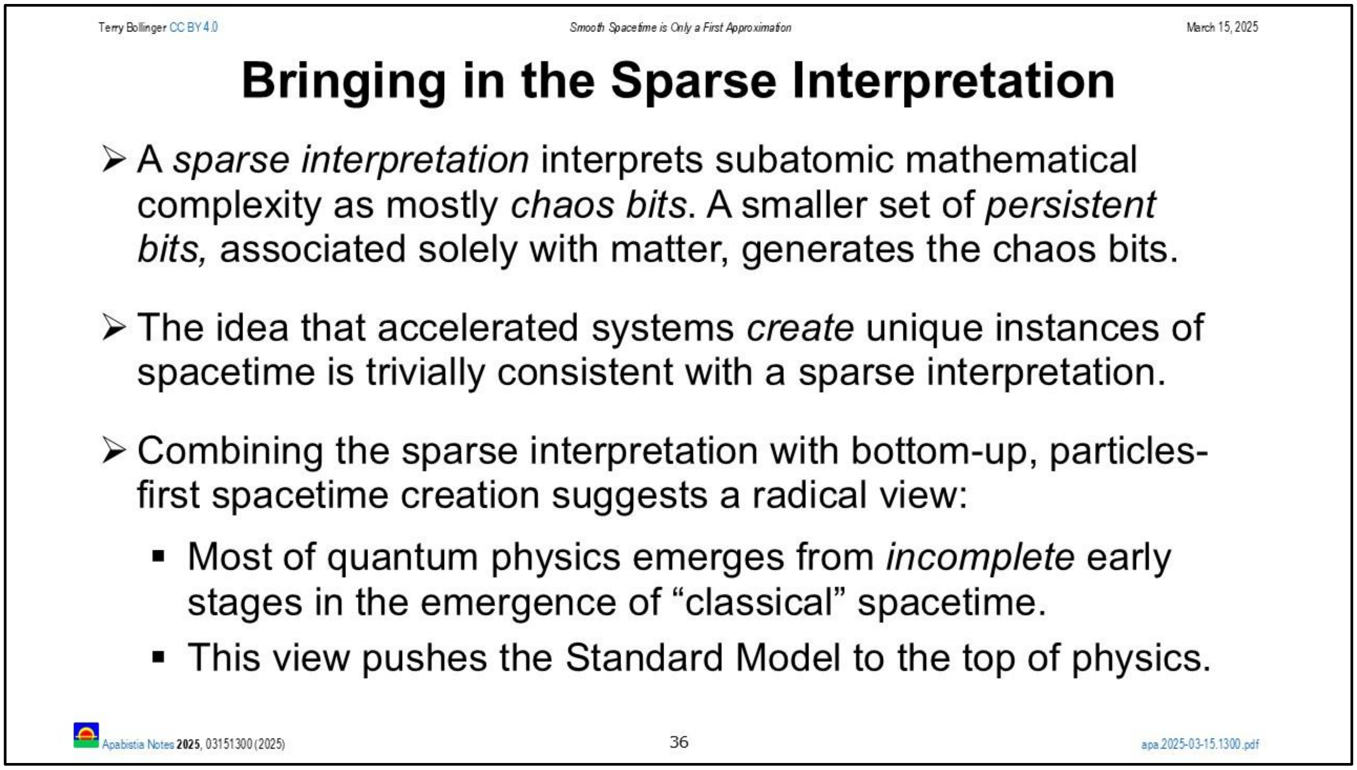
This is incredibly important [for understanding] why spacetime *seems* coherent at large scales. [It] is because you have *fractal restrictions* — fractal in the sense you can do lots of variation in the details, but you can't get outside of the branch that you're on.

This is what's going on with these little [matter-attached inertial frame] cones that have their own definitions of physics. Each accelerated [matter] unit has its own definition of physics — has its own little light cone of things that it *could* influence with that definition [if they could extend beyond the boundaries of their encompassing larger cone] — but those definitions never *get* [to that larger-cone boundary]. They *approach* it, but that boundary is growing at the *same* rate that *they* are growing. So, you *never* reach that boundary. You always have this constant inclusion of the different domains inside of each other.

And that's powerful, because that's why we can look at the universe and say, "Wow it seems like it's all one giant spacetime!" Because in one sense,…it is. There's coordination [within and between] galaxies, and [coordination even] on larger scales, that is sufficient [to give] this *broad* fractal definition of what time is. But then, you [also] have a lot of details [you can explore] as you go down farther [on the size scale toward solar, planetary, human scale, and still smaller inertial frames].

Now, push that [scaling] out far enough [at the large end], and I would not be surprised if you see some problems [emerge]. It's one of the reasons why I'm not very interested in "dark matter" and "dark energy" issues these days, because I think [that] until we get this figured out a little bit better — about how matter instantiates space and time at those scales — we're going to have trouble getting reliable definitions of what we even *mean* by "dark matter" and "dark energy," especially dark energy.

So, more work needs to be done on [the fractal structure of spacetime]. But I love this idea that it's all constrained — it all has a certain coherency — [in which] each [mass unit inertial frame also] has its own definition [of space and time]. [There is] a lot of [analytical] power in that [kind of multi-scale model of spacetime.]



[1:09:33] Last month, I talked at length about the idea of *sparse interpretation*. For those of you who were not on that talk, it's a very simple idea:…The universe has a certain number of persistent, stable bits, mostly captured by particles like fermions. The number of bits is mass dependent, [and] the number of bits is *finite*.

(When I say "bits," there's actually a distinction I would make: There is *persistent information*, and then there are actual *bits*, which are a little more complicated version of [persistent information]. But either way, you have only *so much* persistent information, [and] that is determined, quite nicely, by the total mass-energy of the universe.)

[Given that,] then *all* of the [smaller information] domains where you talk about *Planck scale* — where you talk about *smaller units* [of transient, heat-like information] — all of that] is *created* by interactions.…

Take a proton. It's sitting there, it's minding its own business, it's very, very happy, [and] it doesn't show any obvious structure. You *slam* it with an electron at a *gigantic* fraction the speed of light, and, all of a sudden, *all sorts* of details emerge.

Instead of saying that those details were there *all the time*, a sparse interpretation says you're *creating* those details according to a set of rules. The *rules* are what matter, and how [they cause the proton to] react and respond [to the sudden energy input]. But the details were *not there* until you did that.

This is fairly radical in the sense [that] I'm saying that superposition [as it] is [most] often used — [for example, interpreting] electron orbitals as actual [sums] of [real, particle-like electron orbits] — is not a good picture. [That's] because [each of] those [pure point-like] electron [states] would take infinite energy. [That's true] even to create just *one* of those supposed…components of the orbital.

So, [the sparse interpretation instead] says [that] when you see an electron in a hydrogen atom, *that's about as small as the electron is going to get*.

[Thus] the electron [in the sparse interpretation] is something a little bit different. It's *not* a particle, but you can tie it down into a very tiny package that, to us, until recent times [in human history], *looked* like a particle [because the] atomic scale [at which it exists] is so incredibly smaller than the scale at which humans exist.]

[So, the sparse interpretation] is a different way of looking at physics, and it's very addictive once you [start] realizing [that] every time you look at a problem, you [should] say, "How much energy did you add to see that?" [If they] always say [something] like, "some *tremendous* amount," that should be a warning. It's saying that that [you should instead be] looking at in terms of what's the *minimum number of bits* that could account for all this complexity. And *that's* an interesting problem, because then you start looking at [the problem in terms of a much smaller set of persistent bits — and that is *hard*.]

This whole idea of matter creating spacetime works very much with that perspective. [That's] because [the sparse interpretation] says each system of matter literally creates its *own* definition of spacetime and physics, down to the quantum [level], down to the level of quantum chromodynamics — the whole bit.

Granted, [most of] these pieces we're doing fine without [any need for] doing [a sparse interpretation.] But if you want to *measure* [some physics experiment precisely], you're the one in that [metrical] system. You've set up that classical-like physics in that system. [The idea that you as a finite-mass observer system created the spacetime in which these existing pieces of theory work well] goes together very well with [a sparse interpretation.] It's saying that [the] spacetime [you are using is] itself is an aspect of this sparse interpretation of physics [for *your* finite set of spacetime-defining persistent particles]. [Your definition of spacetime is] literally being *created* by those persistent bits [that obey only the space and time metric definitions of *your* inertial system.]…

Also — and I like this the most! — [the sparse interpretation] says that the Standard Model of physics — which has been around for a long time [and] is *extremely* successful and *very* well tied-down in terms of its predictions, [though it is] unsatisfying in terms of some of the details —… is actually at the *top* of physics. [This is] the idea that things like Special Relativity and General Relativity are *not* [fundamental] things that are pre-existing out there [and were somehow responsible for] *creating* the Standard Model. [It] is the other way around!

[That is,] the Standard Model is using some kind of [deeper] physics that we *don't* understand well — [and] we really don't, because we've been trapped in this thing of looking at the chaos *first*.

But, [the sparse interpretation] says that the Standard Model is based on some [deeper] physics, and *from that* [deeper physics, by way of the Standard Model,]…these concepts of space, and time, and even of General Relativity [emerge.]

Terry Bollinger CC BY 4.0 *Smooth Spacetime is Only a First Approximation* March 15, 2025

Żenczykowski on Spacetime Emerging from Matter

Piotr Żenczykowski,
Quarks, Hadrons, and Emergent Spacetime,
Foundations of Science **24** (2), 287–305 (2019).
https://arxiv.org/abs/1809.05402

"… with space viewed as an attribute of matter … one should start not from discrete (or quantized) space but from discrete (or quantized) matter. Hadrons seem particularly relevant … as the hadronic mass scale is much farther from the classical realm than the Planck mass scale, which is essentially of classical size."

"… the hadronic spectrum parameter [justifies] emergence of internal quantum numbers of weak isospin, hypercharge and color [from a phase-space]. This picture is … unique in its parsimony [and thus] very attractive. It suggests an extension of the concept of mass [and] questions the idea of ordinary divisibility of space … and suggests that standard ideas on intra-baryonic space [only] approximate reality."

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[1:13:47] One physicist — and, Piotr, I don't know if you're out there. I hope you are, but maybe I'll send this to you later — a physicist who's done some marvelous work on just this issue is Piotr Żenczykowski,… a marvelous fellow. He has explored this, and looked at this idea, and said, "You know, maybe we're focusing on the wrong idea."…

For instance, [regarding] the Planck scale energy, he made… an interesting argument [based on the observation that the] Planck scale energies are actually *massive*. They're classic [in scale]! They're… the size of [a large human cell, such as an ovum] in terms of their total [mass equivalence].

He's saying, "That doesn't seem right. The balance seems to me more at the *hadron* level." So, he has explored this idea that the hadron level is related to the idea of spacetime.

I've explored the same idea from a from a different angle when I do something like those [Glasow] cube figures [showing] how hadrons relate to each other. [Regarding] the fact that we have three color [charges] and the fact that we have three spatial dimensions, I would *strongly* hypothesize that that's not a coincidence — that there's a connection going on with these things.

This is where physics could really do some interesting exploration, is getting into this idea of, say, "If matter is always creating spacetime, then how is it doing that, and what is actually [going on in the deeper, pre-spacetime physics] below?" This gets into some interesting issues.

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What is "Spacetime"?

- Spacetime is a set of *relationships* between entities that are:
  - Persistent (highly conserved, not easily destroyed).
  - Devoid of spacetime shape (*nirakar*, निराकार, Sanskrit for "unformed").
  - *Neither* point-like *nor* wave-like. Points and waves are short-term transient views (chaos bits) created solely by interactions with frames.
  - Capable of mutual exclusion (Pauli exclusion).
  - In large numbers, capable of shaping exclusion into *orthogonalities.*
  - Capable of stability, that is, of forming new persistent relationships.
  - Capable of change, which can organize into an orthogonal *time* axis.
- Spacetime is *hierarchical* with *fractal* self-symmetry.
- Spacetime *does not exist* without matter (matter's "address book").

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[1:15:25] What is spacetime? Now, if you follow this viewpoint [I've been describing — that is, that spacetime is locally emergent, combined with] the sparse viewpoint that that there are only so many persistent entities, [you end up with a very different understanding of what spacetime is.]

[At the lower end, you get entities] that we don't understand very well. They're highly conserved, they're not easily destroyed, [and] *they're not point-like*. The whole idea of "pointiness" is a *transient* condition. If you release one photon from any kind of device, that photon *immediately* stops being anything remotely like a particle. It is, by all accounts, by all experiments, a wave expanding at a very large rate. And then, [somehow,] it winds up being *pointy* again!

To say that that's one of the persistent problems of physics is an understatement. But part of the resolution is going to have to deal with this idea that we're *not* understanding the *non-point-like, non-spatial* physics that's going on beneath in which the photon is perfectly happy with what it's doing and not about to destroy itself until it gets to the right set of conditions. But at *that* point, it starts *looking* like something point-like.

So, a lot of these point-like things we see that in classical world [make] point-like [behavior look] easy. [But] as soon as you get down to the small scales, [maintaining a point-like appearance] starts getting *really hard*. You have to observe the thing *continuously*, like in a fog chamber, to get it behave point-like.

[Additionally,] spacetime has some kind of relationship with Pauli exclusion. As soon as

Einstein said, over 100 years ago, "You've got to have rulers or you can't measure space," he really was pretty much invoking Pauli exclusion. Isn't that interesting? [It's] because the only way you can make a ruler is by using this principle of Pauli exclusion, electrons reject each other, and in doing so create a space-like concept. Then, as it gets more complicated [with greater numbers of these persistent entities], you get these extraordinarily stable relationships that we then expand into our definitions of space.

So, [when it comes to creating spacetime,] numbers count in these things. If you have a lot of matter, you can get a very smooth definition of spacetime. [Conversely, it] you don't have much matter, that gets *interesting*. You start [having to] say [things] like, “How much spacetime can I create with, say…just one electron?” Or, “How much spacetime can I create with three quarks?”

Piotr [Żenczykowski] explored that. He thinks the inside of a hadron [is not ordinary space, and he is] not the first one who’s talked about the idea that the inside of a hadron is not what we think it is…not ordinary space. We can impose that perspective on it, but [the alternative is that such spaces are] something simpler, not as complicated. I think he’s really on to something.

So, the other thing [about] spacetime [is], I would argue, [that it] is hierarchical. [That is,] it has fractal self-symmetry. We have groups of matter that work together and create coherent definitions of space and time. But then you get new subsets moving within that [larger group that then] have their own definitions of space and time.

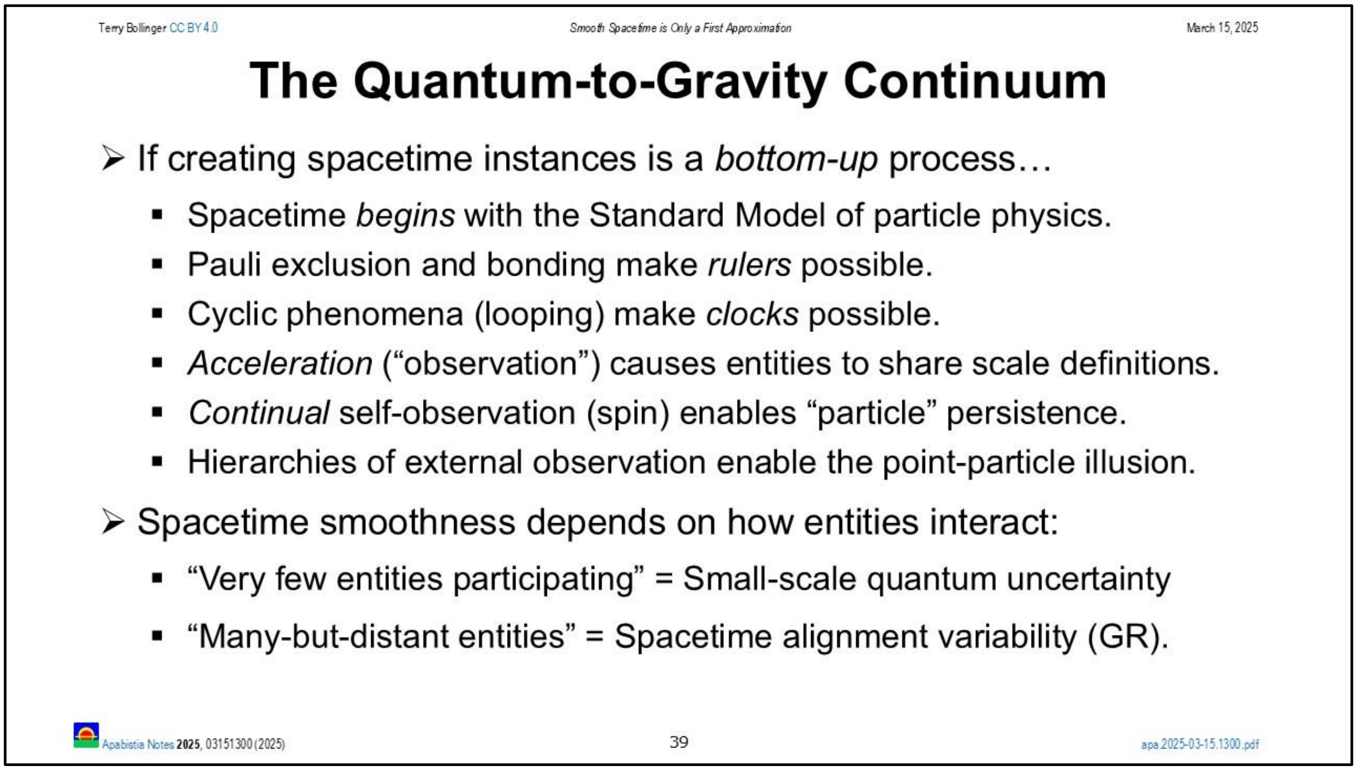
The final point — and I can’t emphasize this enough — [is that] if you don’t have *matter*, you don’t have *spacetime*.…

I mean that in the most literal fashion possible. *What are you going to measure it with [if you don’t have matter]?* You can say that spacetime *is* [the essence of] matter, and I guess that’s one way you can argue it. But the bottom line is [that] you get [into] this curious [situation in which] you keep talking about measuring spacetime without any instruments with which to do that.

This also gets in the issue about…the density of the vacuum. If you listened to my previous talk, I’m absolutely on the side of saying the vacuum is exactly what people thought the vacuum was for millennia: It’s nothing — just absolutely nothing. There’s no boiling, frothing, Casimir-generated foam out there. That only happens in *matter*, and [even there] it’s strongly limited by the [total energy available in that] *matter* — which is a really interesting aspect that even Casmir noted indirectly.

So, spacetime does not exist without matter. That’s a big flip [since] it’s very easy to go the other direction [and assume spacetime is more fundamental than matter.]

[However,] I always saw [that] other direction [as far too] complicated. Why would something as [complex] as spacetime be fundamental? It is *really* [complicated]! How do you get that [complex of a] set of relationships [to exist] spontaneously? So, having [these relationships] attached to the matter certainly helps [explain the complexity of] special relativity, and I think gives a more coherent view.

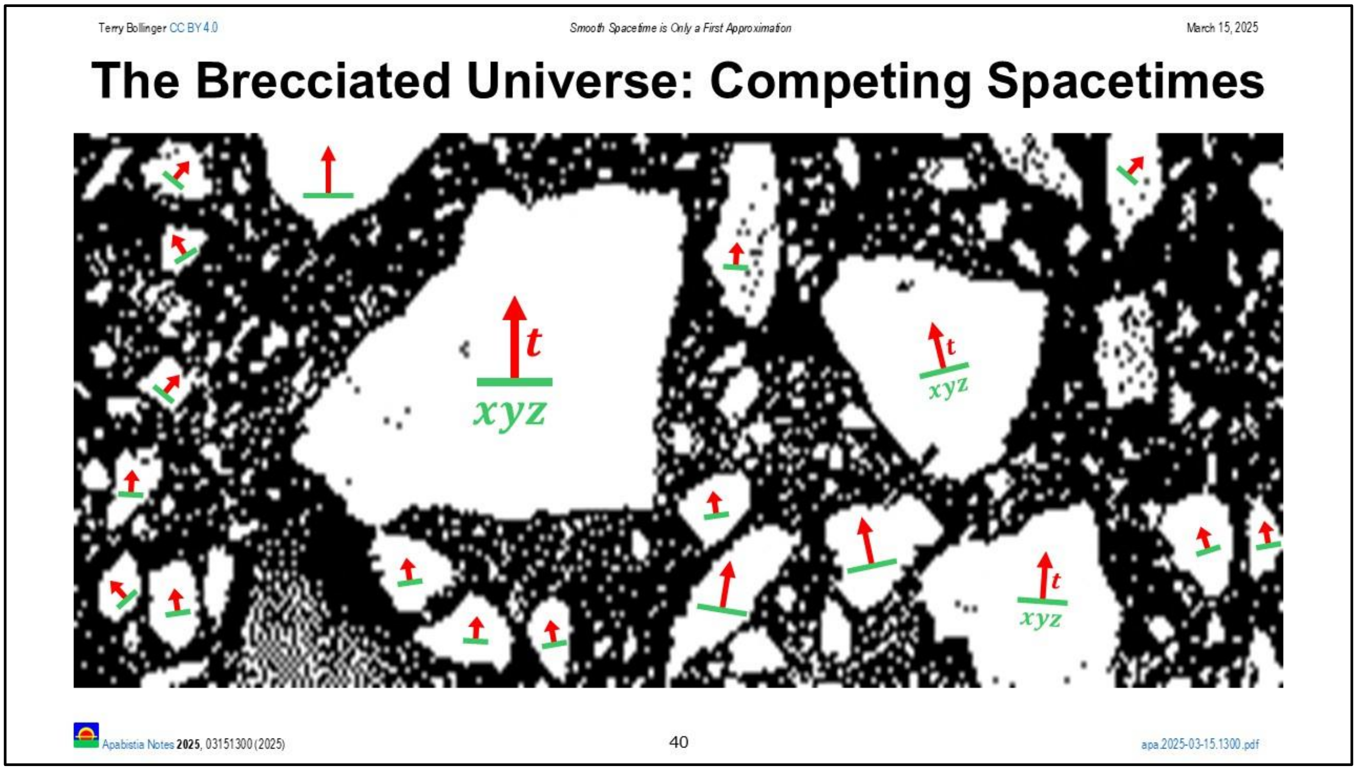


[1:20:04] So, this gives you an idea that spacetime is a *bottom-up* process, [including] the idea that spacetime *begins* with the Standard Model [of particle physics], Pauli exclusion, and these other factors — cyclic phenomena that make clocks possible.

Constant self-observation is how you get this illusion of particle-ness. That’s also a *huge* part of why this works — this whole idea of self-observation. And again, for folks who don’t know it, for me, observation is *not* something magical. It’s just bumping! It’s about as unmagical as you can get: It’s acceleration. Every instance of acceleration — in part for some of the reasons I’ve talked about here, [such as] the fact that any acceleration introduces conflicts in the definition of time, [and] at a minimum, that’s pretty good right there — acceleration is *critical* for making things suddenly “wake up” and say, “Oh, I’m part of this system, and I’m supposed to be *here*, according to the rules that I’ve been following.” You do that enough, and you get very self-consistent definitions of things that look particles. But they’re never *really* particles. What’s going on beneath is ill-formed and doesn’t align with our usual concepts of particles *or* waves. Those are *both* hyper-classical concepts.

So, if we don’t have *enough* of these entities, surprise, surprise: You get uncertainty. Why? [Is it] because [we have] an “infinite number of universes, infinitely competing infinitely, all the infinite time?” No! It’s because you don’t have enough resolution — you don’t have enough details. If you look at *one* pixel on a screen, you don’t get much information out of it.

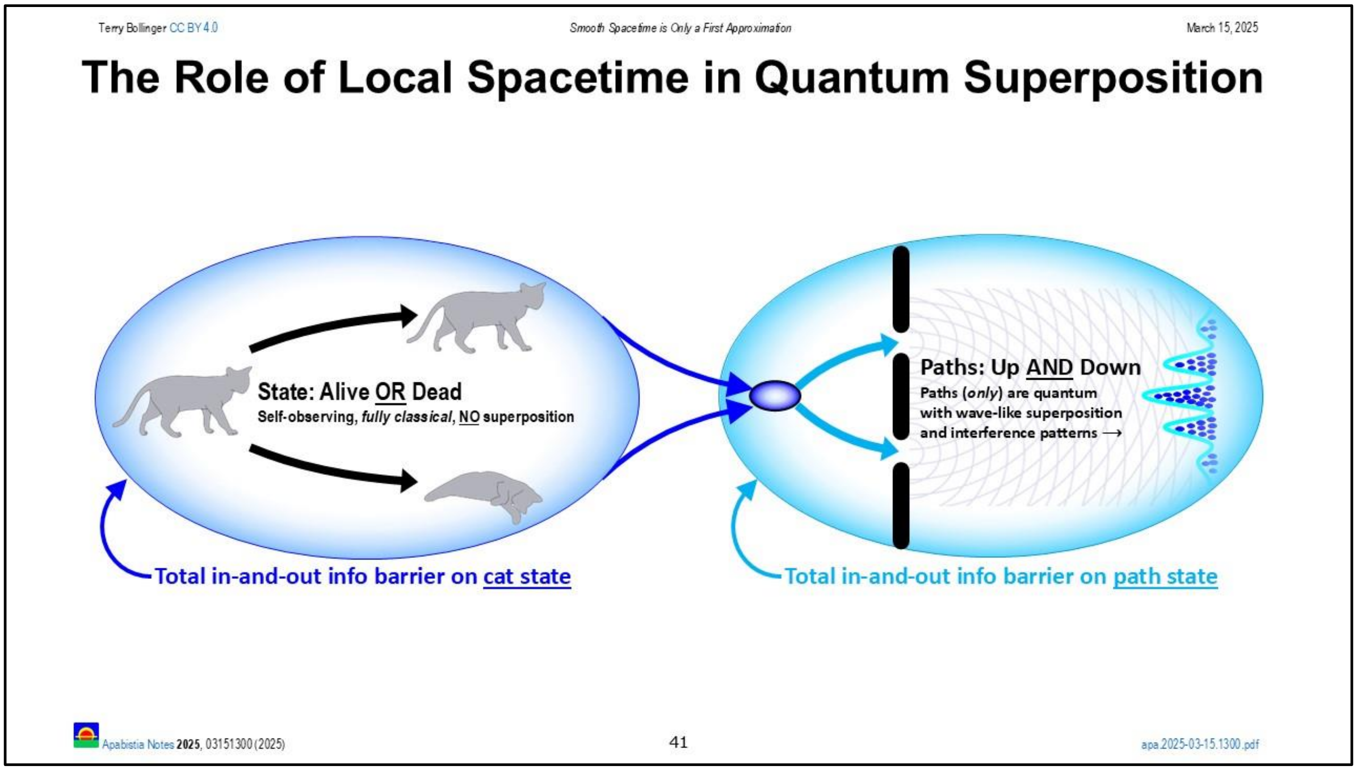
That’s all this is. I think we’ve bloated quantum uncertainty into a *far* more complicated topic than it needs to be. [It’s mostly a lack of information in a given situation, although] space alignment — [how these diverse and multi-scale definitions of matter-connected spacetime align with each other] — is [also an important and possibly dominant source of quantum] variability in all of this.



[1:21:55] If you look at figure, this is just kind of throwing out the idea that, if you work this out, you get a brecciated [structure]. A breccia is the kind of rock [in which you] have these "clasts" — these little chunks — of different definitions of spacetime.

I think something like this is a better view of how the universe works. This is why I think, if you look in the *large* scales of all these cosmic filaments and these strange things going on, I think we're seeing something more like *this*. You're just getting different competitions — different *definitions* — of space and time that are… *sort of* keeping up with each other? But after a certain point, they start *losing it* because they're so far away from each other. The ratio of empty space to matter gets so high that [these cosmic structures] start getting string-like, [or] they start getting sheet-like. [In other words,] they start *losing* dimensionality — they start doing *strange* things. I think a brecciated universe is probably a more interesting path for figuring out where some of these [cosmic structures] might come from.

And yes, this is a huge scale-up or elaboration of [the small-scale of special relativity examples]. But you can't get away from the fact that, even in those smallest examples going all the way back to Einstein's [time transformation] equation, [that] once you have [added] that length parameter [to his time transformation equation,] you have attached [spacetime] to matter. And once you attach [spacetime] to matter, things like this [brecciation] can [(and must)] happen.



[1:23:12] Oh, and [there's also] quantum superposition! This is something that, if you're creating space and time [*locally*,] gives a whole different twist on some [key] ideas of [what quantum] superposition [is].

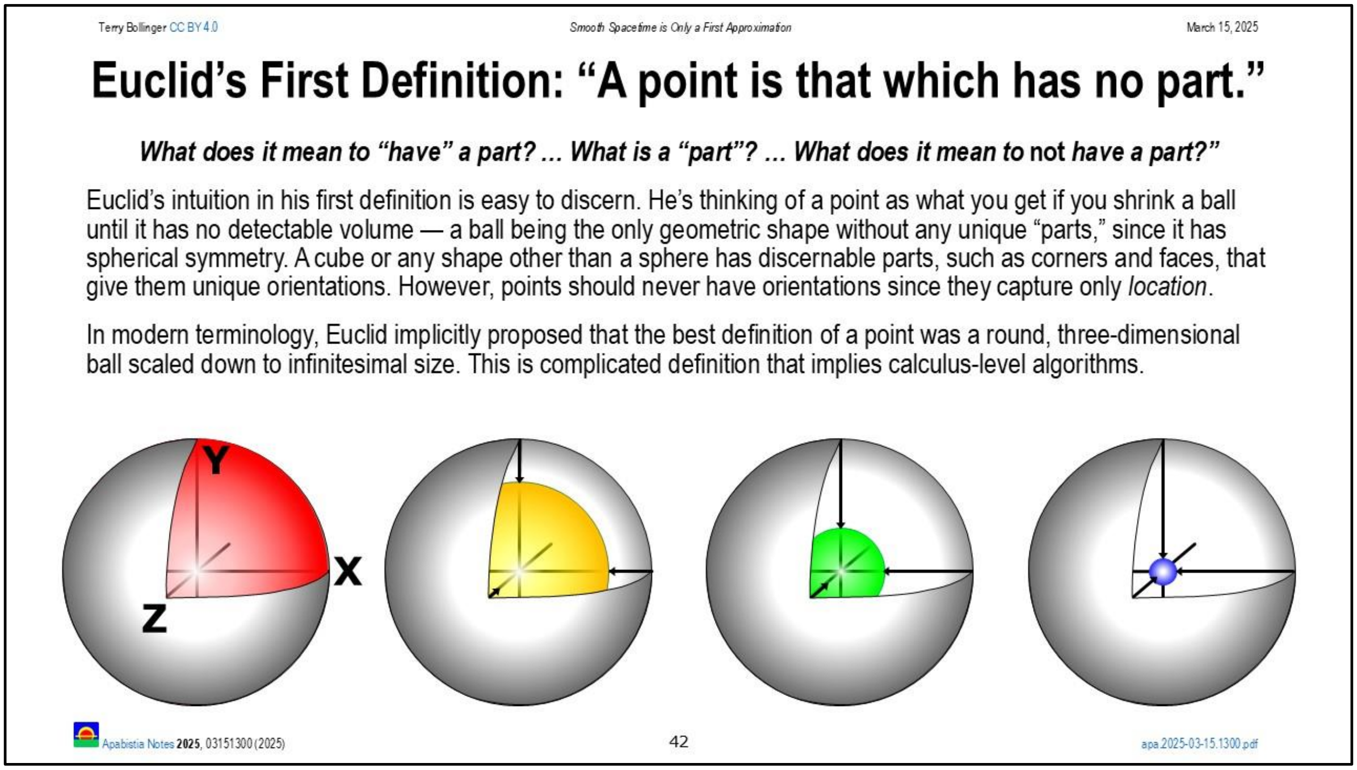
The biggest [implication] is this: Many [experimental observations] that we call "superposition of state" are actually superpositions [not of objects, but] of *spacetime*. [By that I mean] we're playing games with how we create spacetime locally — and those games look like *waves*. What's really going on with the cat-dead or the cat-alive [question] is — and to me, this just seems to me like an incredibly simple statement, but I'm a little biased — *the cat either dies or lives*. It just *does*.

[What has happened, starting with Einstein's omission of the length parameter that created false histories and thus, also, false spacetimes, is that] we've exaggerated [the scope of] these quantum wave functions to places where they don't really apply. So yes, the cat may have *started* as quantum event. But the cat self-observes, and it either dies or lives.

But — and this is important qualification — if you can keep that cat *totally, completely isolated* from the rest of the universe in terms of information — [information being the universe's] "credit [and debit system" for spacetime, that is,] the way the universe "talks to itself" to [reconcile divergent instances of] space and time — if you can keep [the Cat] isolated, then it will be capable of doing these interference patterns in terms of space and time.

What's really going on there is you're messing with the [after-the-fact] definition of space and time. [Thus, in the double slit experiment,] it's not that [a particle or molecule is] really going through [one slit or the other.] [Instead,] we need to understand better that the physics underneath [our ideas of space and time] don't respect our ideas of travel — not the same way we do. We need to understand that we're just *reconstructing* a path — a spacetime path [created] "after the fact." That [spacetime path] *doesn't always work*, not when you [take into account the different way travel takes place in] this this deeper physics.

So, as Schrödinger intended: dead cat or live cat — it either dies or it doesn't. But keep an information barrier [up], and [it] gets interesting [because *independently of whether the cat dies or lives*, the Cat can still, in principle, interfere or reflect.]



[1:25:17] Now here's [another] one. Since I [keep] beating on this [issue of how math and physics interconnect] and keep talking about the physics of points, [it helps to look closer at how mathematics defines points.]

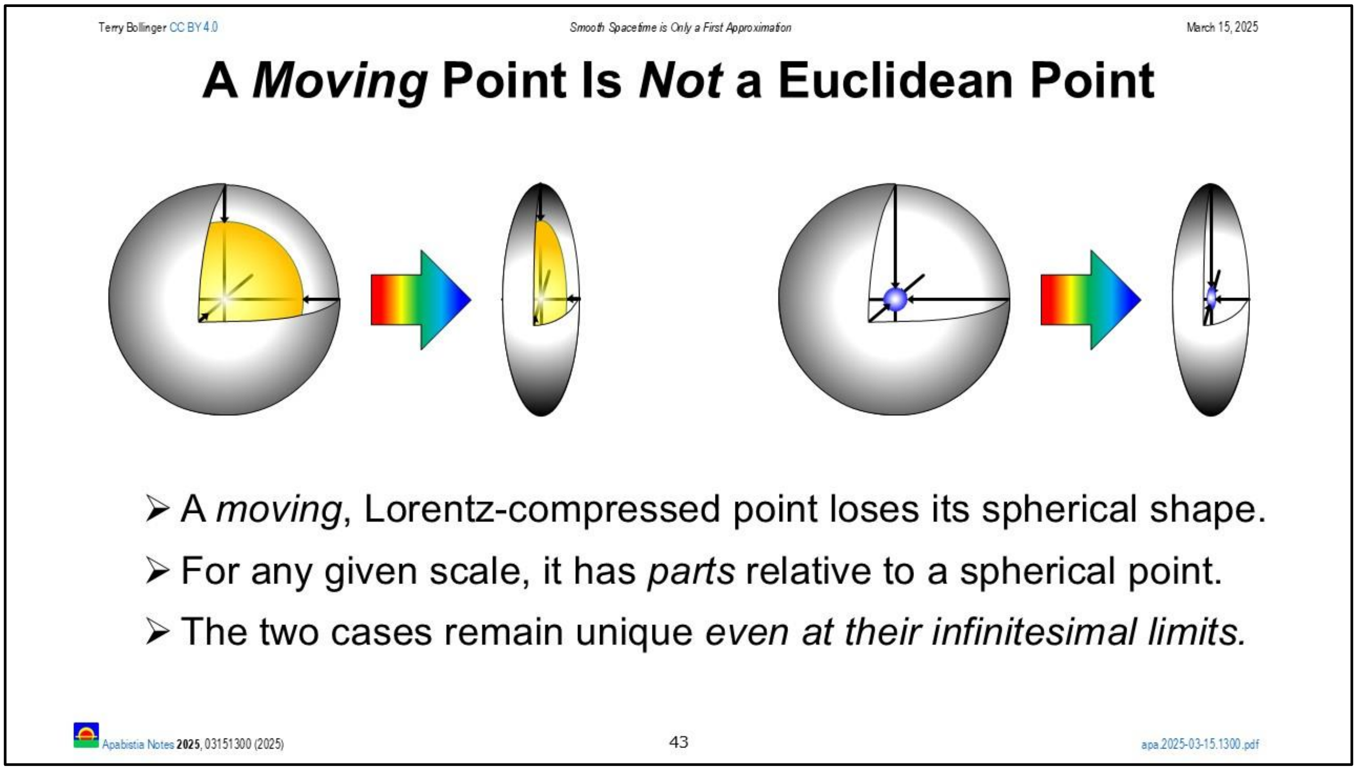
The definition of a point — the *very first definition* Euclid gives — is [that] a point is "that which has no parts."

That's actually kind of uninterpretable, but if you look at it carefully, what he really means is: If it has spherical symmetry and you shrink down the smallest size possible, that's *pretty close* to what [he means when he says,] "It has no parts." It has no information on it — no additional [information, just a] location.

So, that's a clue there to actually implementing Euclid's first definition, which is supposed to be the most trivial part of his entire works. You have to use a calculus type condensation of a space, presumably of three dimensions, going down to some infinitesimal limit.

That should be a warning right there. It's saying that what you're actually doing is following a set of rules that have a nice asymptotic limit, but they don't actually get there — and in physical reality, they *don't* get there. You can take the electron and compress it down to a point as close as you want, but it *fights* harder and harder as you go down.

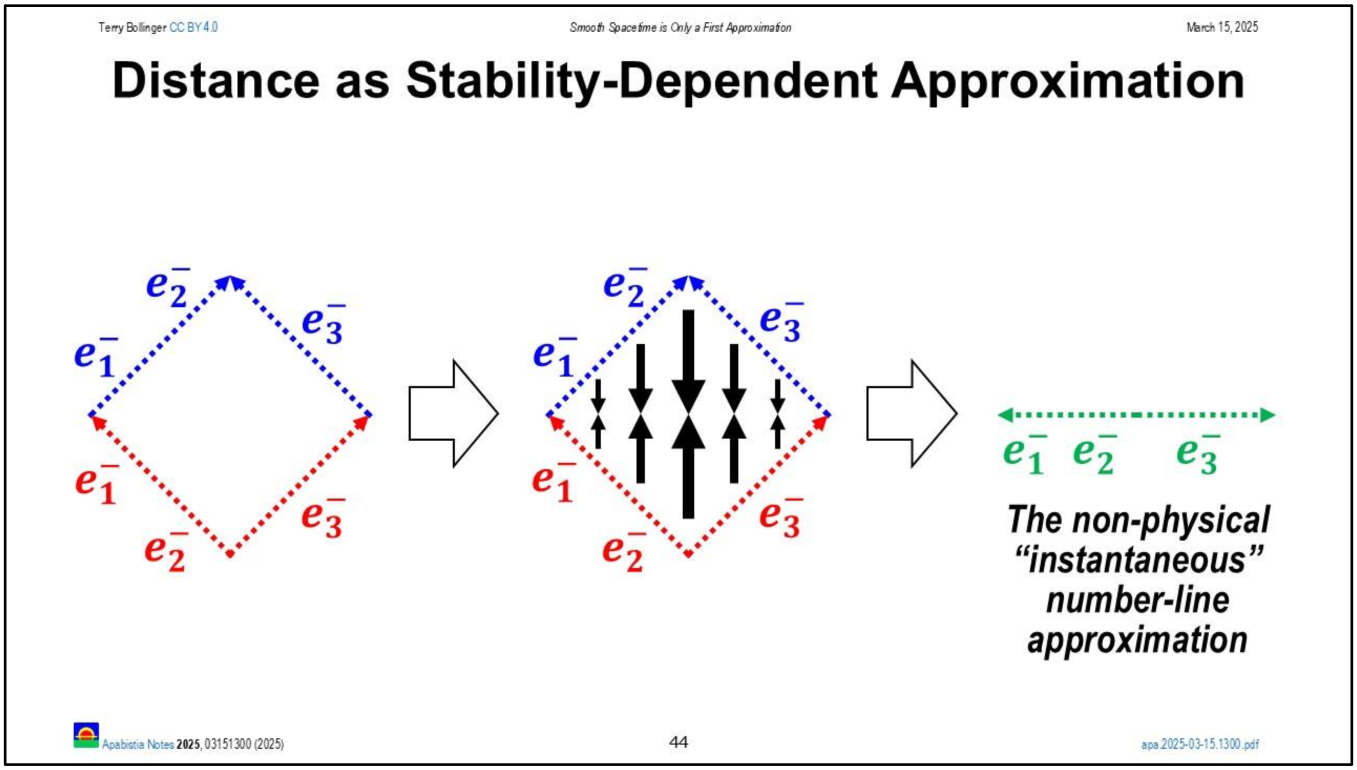
So, when you talk about a region of space having definitions of physics, classical physics points are part of that, [and] electrons are part of that.



[1:26:47] In fact, if you look at an electron that's moving by you at a high speed — or if you look at a definition of a point [moving the same way] — then it fails to be a point anymore!

Why? Because it's [a Lorentz-compressed disk in 3D, or a 4-ellipsoid in Euclidean 4D space]. It *has* to be [distorted from a sphere because] this is a real physical change in terms of how it [transformed during acceleration from the rest frame]. You get changes in the conformation of the point, and you have to look at that. If it's disk-like or elliptical shape, is it still a point? And the answer is probably no.

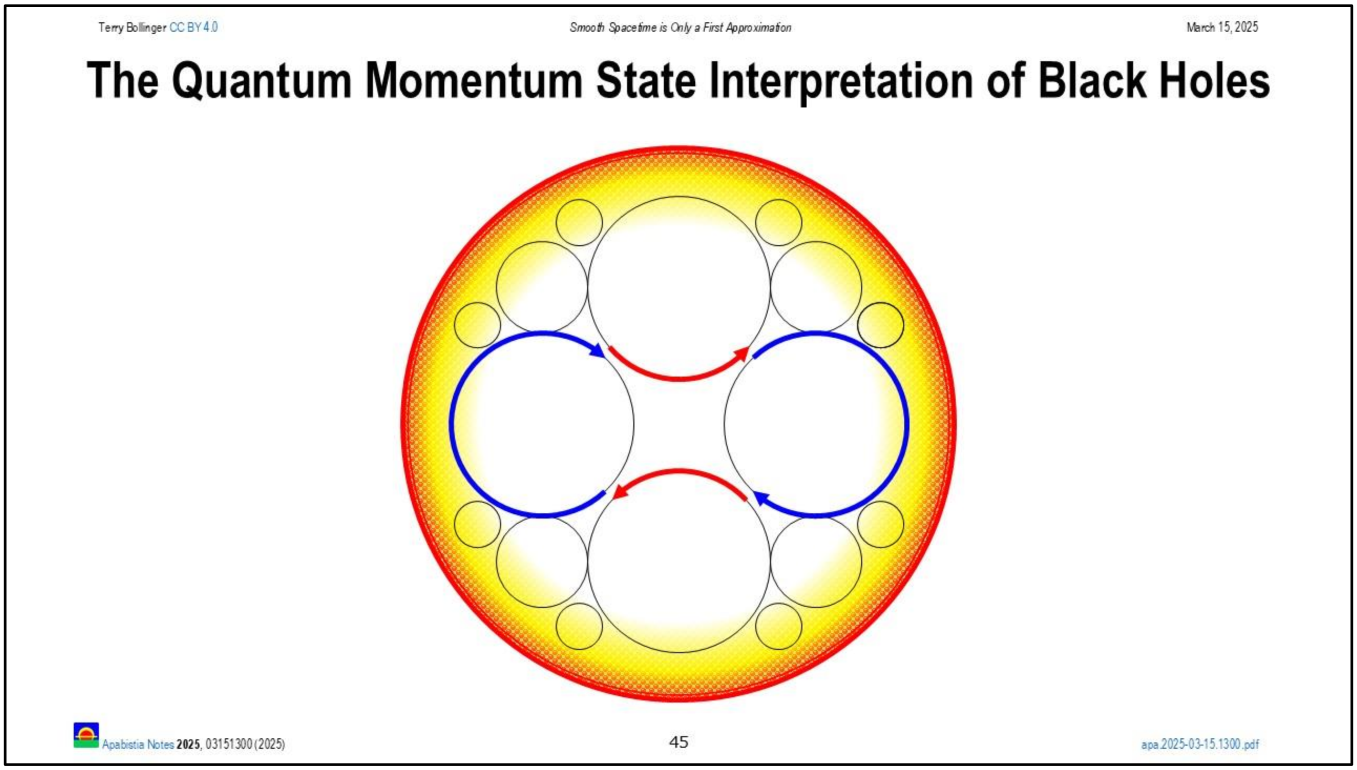
So, the very definition even of a point in mathematics is dependent on having a self-consistent definition of an inertial frame. I find that fascinating! It says that math, all the way down to Euclid's first definition [has ties all the way down] to the idea of a material moving frame, with all the properties that [moving objects] collect [under special relativity].



[1:27:43] A [comment] about distance — just a quick note on that. [In my] earlier slide, [I] said that when you when you look at a distance, you're actually looking at times, clocks, and issues like that. Every time we talk about a distance, we're using a rather complicated abstraction in which you have an assumption of stability across time.

[That is, you are assuming that] the ruler was there [in the past, and that] the ruler is still there in the future. All these things depend on an enormous amount of complex-material persistence. Without that complex-material persistence — the ability to make a ruler — you really don't get that, [and at remarkably fundamental level, you lose the ability to define length and space].

So, just quick comment on that. [It's intriguing and important to realize that the concept of length is] trickier [and more dependent on clocks] than it might seem. ...

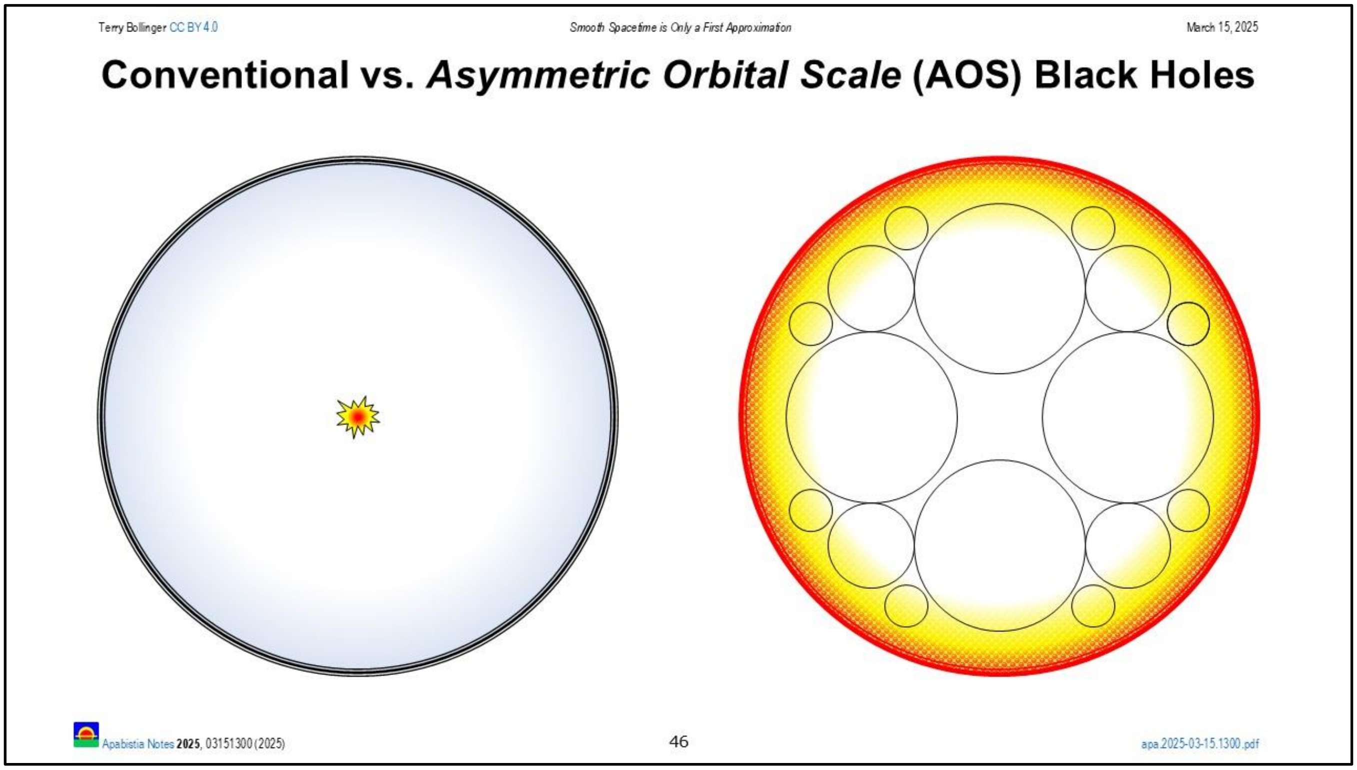


[1:28:30] This is supposed to be a Gerard ’t Hooft antipodal black hole momentum state, [but the emphasis in this figure is more on my idea of (not ’t Hooft’s) that magnification of the interior space of the black hole excludes most particles with angular momentum states from entering the interior of the black hole. The very small number of angular momentum states that manage to reach the interior become the lowest-energy states in black-hole-sized Fermi sea. These spatially enormous interior states force the higher energy states that include the vast majority of infallen particles to reside in the red perimeter shell region we think of as the event horizon.

No particles in this magnified-interior version of a black hole are ever fully out of communication with the outside universe. Also, because particles are more fundamental in the bottom-up spacetime approach, baryon number is conserved. This is in sharp contrast to the idea that black holes erase everything except mass, charge, and spin. While the energetics of the black hole can easily create antimatter, any such creations must be balanced by matter creation. The evaporation process is no longer one of pure energy, and must eventually re-emit particle sets equivalent to the ones that fell in. A notable implication of that is that full evaporation of large black holes may be impossible, with the holes instead cooling down only through photon processes.]

[The concept of antipodal momentum states in black holes] was a fascinating little bit of work that [’t Hooft] did [in 2016], based on [a 1987 paper by Norma G. Sanchez]. [“Antipodal” means] that instead of black holes [dumping infalling matter into] white holes in some other universe, [’t Hooft] and [Sanchez, who] had done this decades before, came up with this idea of [infalling matter ending up at the] antipodes [of the black hole. [Antipodal means “opposite poles,” and thus] is a complicated way of saying that, eventually, when something falls into a black hole, it comes out the other side. [In a much more recent 2018 paper titled “The New Quantum Structure of the Space-Time,” Sanchez proposes that quantum uncertainty erases the boundaries between the four Kruskal regions of the Schwarzschild-Kruskal coordinate system typically used for analyzing black holes. The magnified interior view in this figure accomplished the same goal by enormously magnifying and granularizing the space that traditionally was supposed to form a singularity inside the hole.]

I like how you can get very complicated lingo [and math for ideas like this]. But all antipodal means is that, eventually, [infalling matter] gets [to the opposite side]. In the details, though, what happens it turns into a complex momentum state on the surface of the black hole.



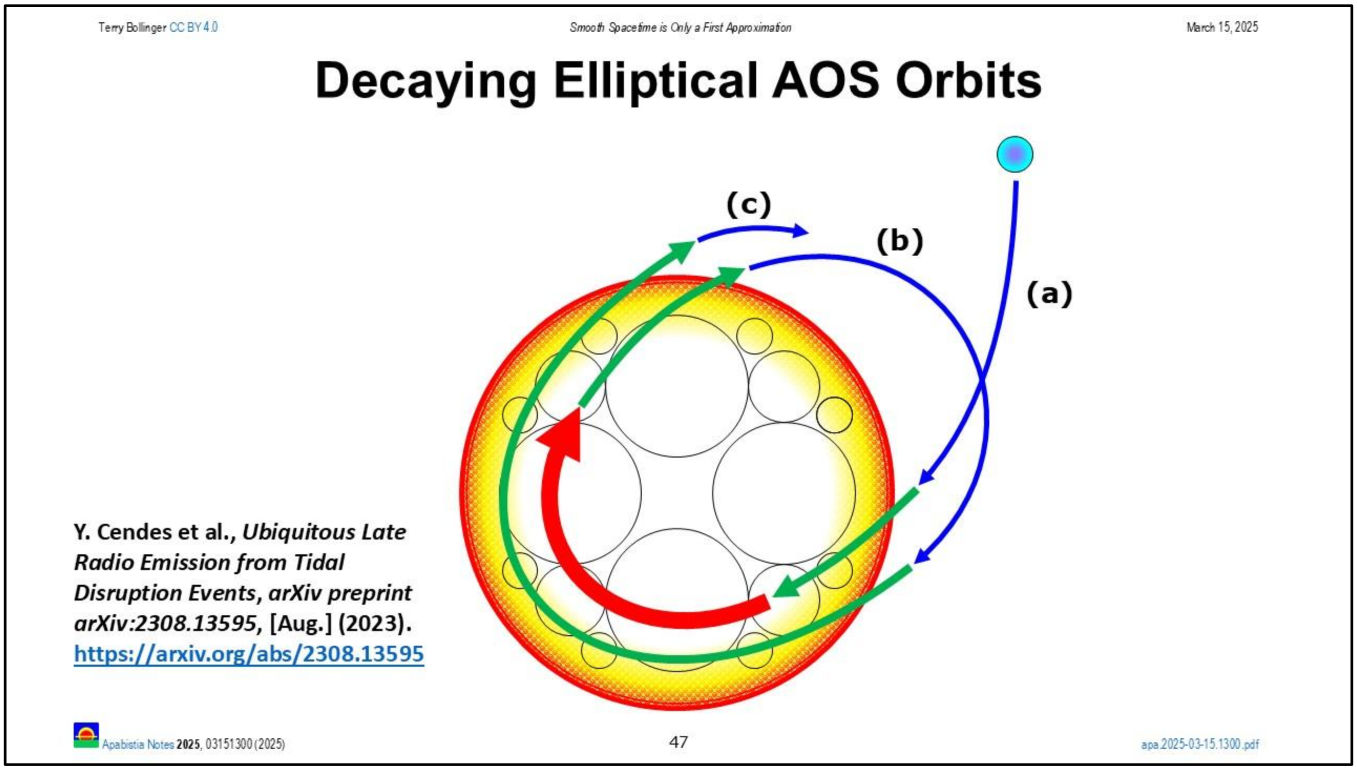
[1:29:27] Now, that leads to [this]: *If you think matter defines spacetime*, guess what? You *can't have* black holes quite as you usually think of them [in Figure (a)]!

[Instead,] you get something more like this [Figure (b).] I call the [resulting set of dynamics] an *Asymmetric Orbital Scale* (AOS). I think that was from [a previous presentation. That's a bit overly specific for describing a black hole as a whole, so] I might change that acronym at some point.

[The idea that spacetime is always a creation of matter leads to this] really interesting different interpretation of black hole if you define curvature space as being a function of matter, which is this: Imagine that the center of the black hole [consists of] spacetime that has been *incredibly* magnified, to the point where nothing can exist [inside] it anymore. Even a single particle is excluded because [the granularity of space] is so *huge* inside of the black hole that there's just not [enough] room for anything.

This gives you a very different internal structure of a black hole, but it also gives you [roughly] the same kind of event horizon surface that [astronomers] see, especially experimentally, on the top [of the event horizon.]

So, this a *very* different way of looking at [black holes.] The whole idea of a singularity just *disappears*. You instead get a really interesting kind of hyper-magnification of the spacetime concept [that is caused] by the *very* dense matter [in momentum state orbit] at the top of the event horizon.

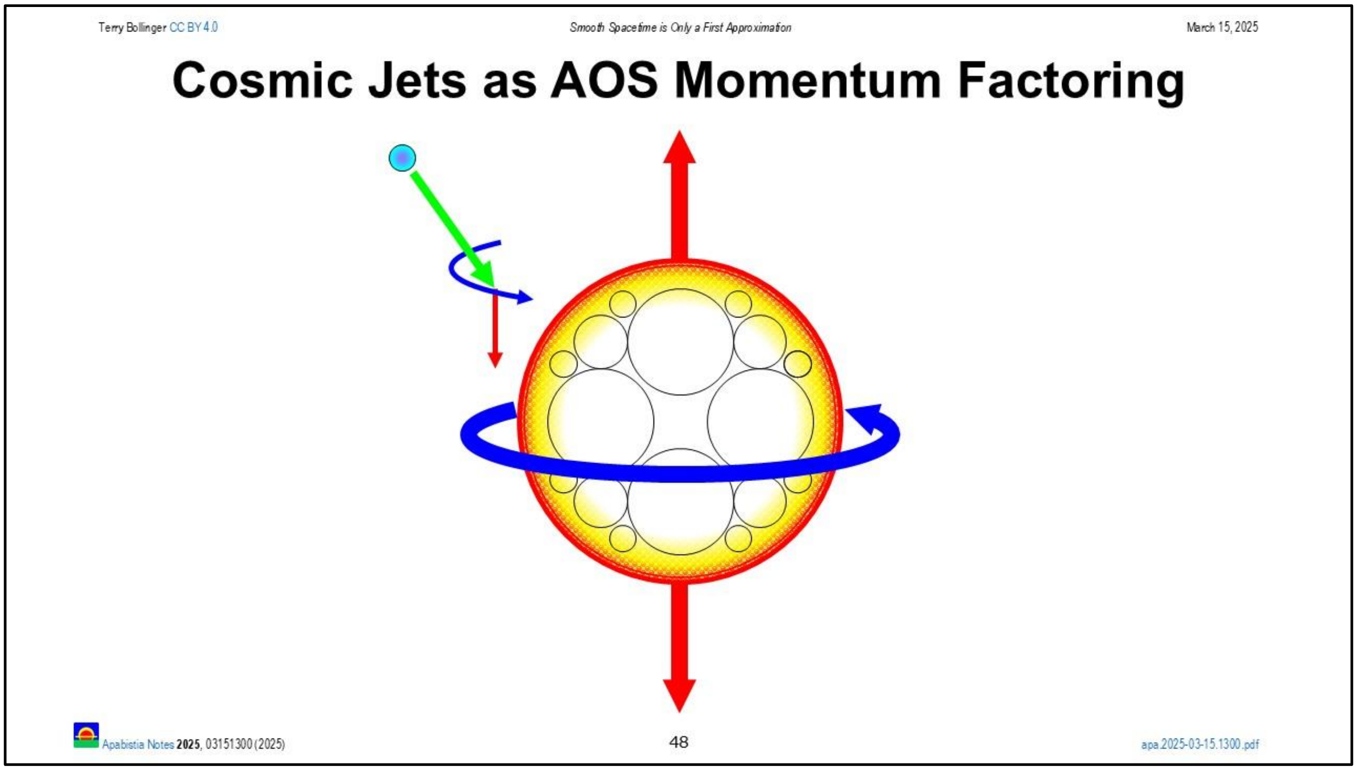


[1:30:50] Now, when I said experimentally, I *meant* experimentally. There is fascinating evidence that when a star falls into a [giant galactic center] black hole that, on multiple occasions, remnants of it emerge years or even decades later, and then continue to [reappear in repeated cycles]. That's not what's supposed to happen with a black hole!

So, that is a very different interpretation of what happens with a black hole. It's an interesting paper. I have not seen follow-up work with that, but I think they're on to something about [the difference between] what we think black holes are doing what they're actually doing is different.

This whole [orbital] angular momentum issue is really important when [trying to] understanding black holes, and [astronomers] seem to be getting some experimental evidence that the internal structures are more complicated than [folks] thought.

[There are also theoretical papers that address the issue of slow, deep orbits for the innermost regions of the black hole accretion disk. In many ways, the AOS model does nothing more than extend these accretion disk models downward to explain the dynamics of the black hole itself.]

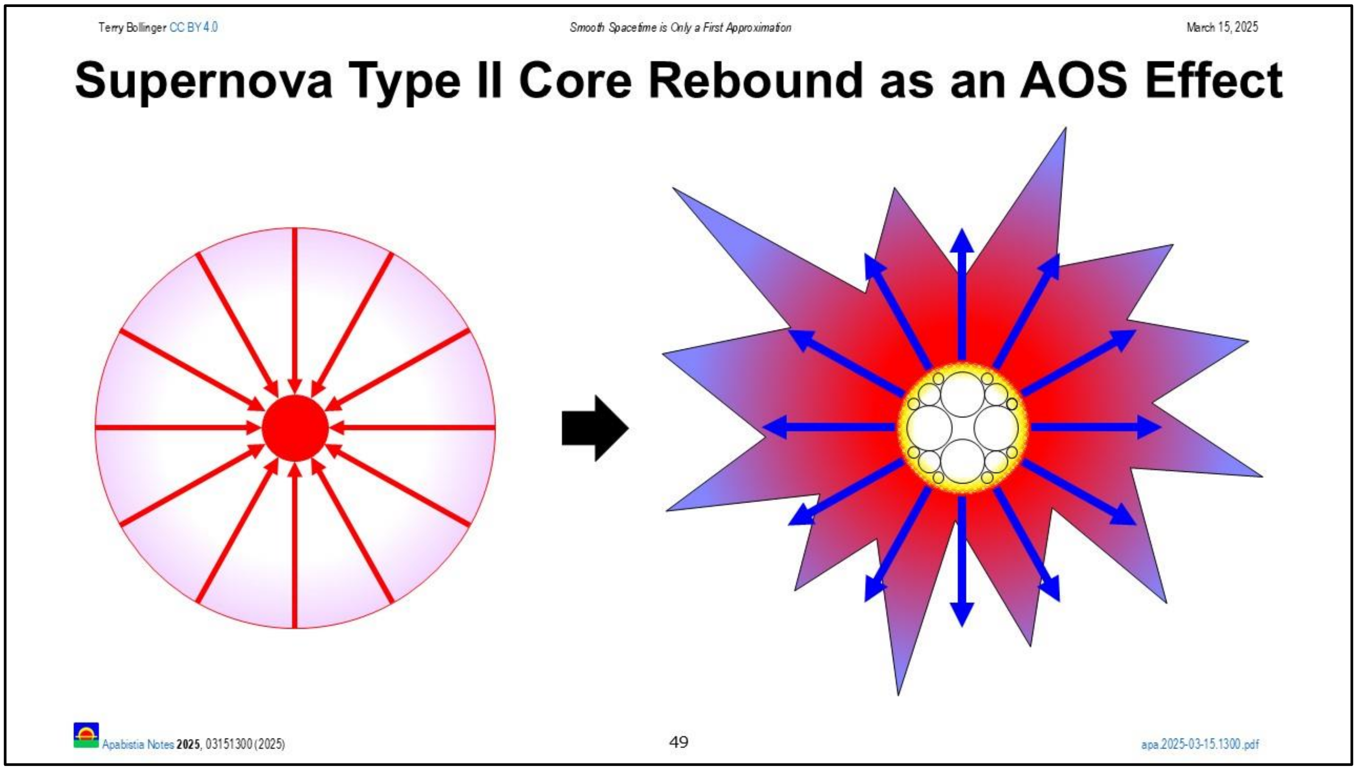


[1:31:46] On that same [topic of black holes], this is just one example of where you could go with [the asymmetric orbital scale black hole model — that is, the model in which the magnified interior space rejects mass from penetrating deeply. This model concentrates the entire mass of the black hole not into a singularity at the center, but just above what we currently think of as the event horizon of the black hole].

When a star falls onto [such] a [spinning spherical shell version of a] black hole, it winds up getting factored in terms of momentum. Think of [the star] as being turned into an almost pure momentum state. You [then] have *angular momentum*, [which] is what the black hole *wants*, and the *linear momentum*, [which] is something that it *discards*.

So, this is a different way of saying that, as you get the green arrow [representing the star's total momentum] coming in, it gets broken down into the blue circular angular momentum, because [AOS] black holes are ferocious on [capturing] the orbital angular momentum. But then it's got that other [axial linear momentum] component [for which the black hole] says, like, "Nah! I don't want that. You get out of here!" [The result is a pair of powerful cosmic jets aligned almost perfectly with the spin axis of the black hole.]

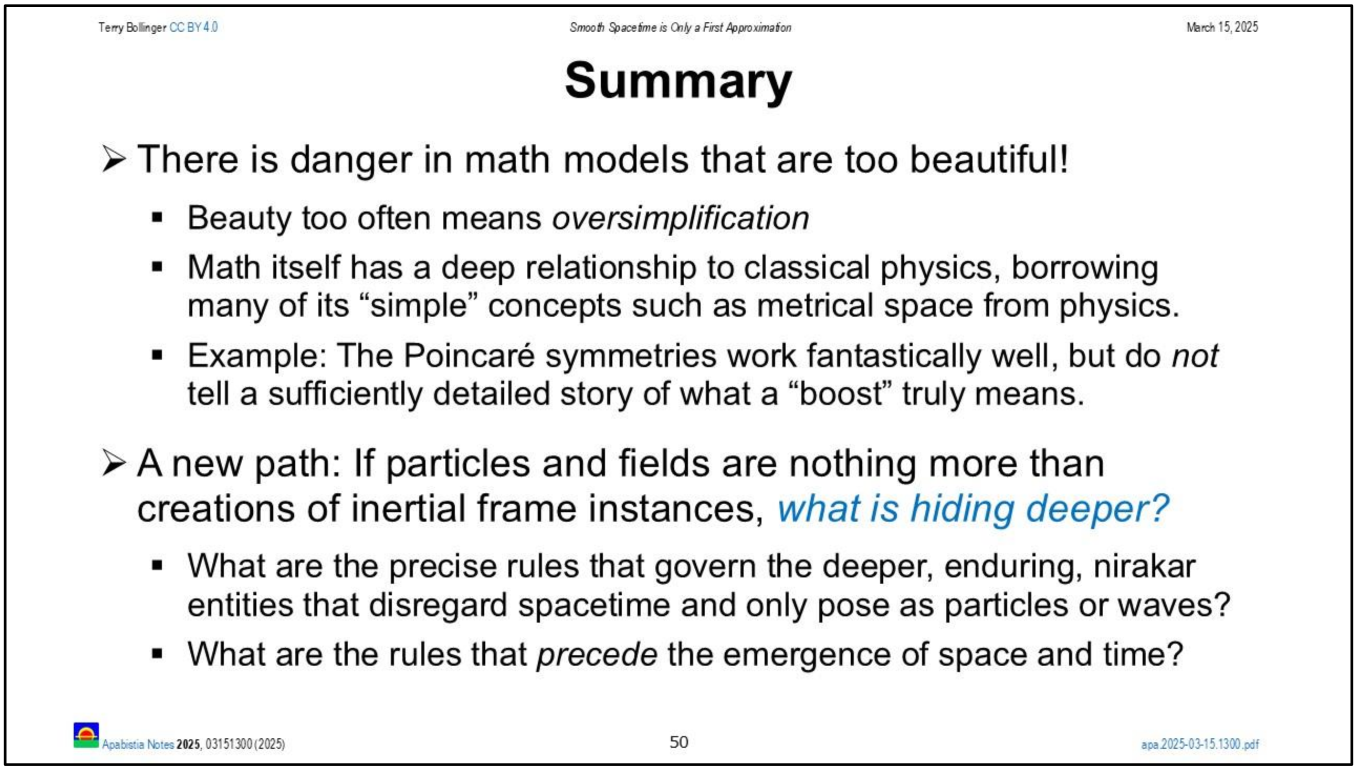
So, this is a very different way of interpreting something like [the stellar jet dynamics of a rotating black hole]. [It's] just an example of [how] taking matter as the origin of spacetime gives you different ways to explore some very interesting phenomena.



[1:32:43] One last one: … Supernova Type 2 core rebound. [This is when a giant star exhausts its final traces of fusion fuel and embarks on an extremely rapid, millisecond-time-scale full collapse towards its center to create a black hole. This collapse process is always accompanied by a powerful rebound in which much of the mass of the star ends up not in the black hole, but blown back out into space as a supernova. This rebound component] has always been a bit mysterious. How does this [star both] *collapse* and *bounce back* so ferociously?

Well, if a black hole is *not* a singularity, but a resistant chunk of hyper-magnified spacetime in a very small unit, you are *going* to get *rebound*. So, [the idea that matter creates spacetime] gives you a very different take on [Supernova Type 2 rebound]. You're going to get accumulation of the matter around the [black hole surface, where it becomes mostly invisible to the outside universe], but you'll also get a powerful resistance to anything truly falling *all the way* into [the interior of the black hole].

The previous result I mentioned, where you have stars *popping back out in pieces* years later, kind of goes along with this idea. It's saying, like, "Oh, it's *harder* to fall into a black hole than we thought." You can get slowed down [in the process of falling in], but [actually crossing into the black hole interior is] not as easy as [folks] think. [This is in sharp contrast to the decades-old Kip Thorne "easy crossing" model. That model relies too heavily on Kruskal coordinates that let folks pretend the singularity disappeared simply because it's been scaled and folded into a single tiny point at the center of the coordinate map. This bit of non-physical, visual-figure-scaling magic makes it too easy for folks to fool themselves into thinking entry into the interior of a black hole is easy. It's not.]



[1:33:34] All right! Wrap up. Math is great, but simple math is often just that: It's too simple. Poincaré symmetries are beautiful, but if they *don't track the actual sequence* and all the complexities that go on with what you're doing, then you want to *examine* whether you need to have a more complex model.

I would say that, in the case of acceleration, we *absolutely* need a more complex model. The idea of reducing everything to a "boost" [just doesn't cut it.] There are certain cases where that's useful, and it's certainly handy, but it doesn't *tell* you anything [about the deeper structures of spacetime that only acceleration exposes], especially if you're trying to understand the deep details of what's working.

So, the part of physics that I think is the *most* fascinating, and probably the most productive — assuming that what I'm saying is correct… you know, if you buy the idea that sparseness is a good way to go and buy the idea that space and time are created *by* matter rather than vice-versa — if you follow that route, then it says there is a *whole domain* of physics that we have *barely touched*. We glance off of it when we talk about quantum physics and entanglement, but only in a very clumsy fashion.

The term I've used a few times is "nirakar," which is a Sanskrit term for *formlessness*. Whatever the physics is that going on below this level, it has endurance; it has persistence — *after a point*. But even the *persistence* is an emergent property There's some combination of these things that wind up giving us this marvelous set of classical capabilities — classical physics capabilities. But there has to be *construction* [to get] there.

It's a hard domain to think about! If the *first thing* you throw out is *space and time*, then you go, like, "Well, how do I analyze *anything*?" It's a good question! But, it's also one that you want to look at more closely. Are there principles that hold? Absolutely! Conservation is certainly a *huge, huge* factor that *never* seems to vary. So, the conservation of various quantum numbers is a resolute part of whatever this underlying physics is. So, there are some starting points.

But the idea that classical ideas of space and time emerge *from* that? That's going to take some work! But this is also where I think the most power for issues like quantum computing comes from, because whatever this underlying physics is, it is *neither* waves *nor* particles, nor exactly what we would call *quantum*, but something, really, more nebulous than that. *That* has potential — some powerful potential. Biochemistry seems to make *some* kind of use of it, because biochemistry is *always* calculating things we can't do. That's why it takes us gigantic computers to model *one silly molecule*. So, there's some potential there.

And with that, I'm probably *way* over, and I will call it quits.