Operational Simultaneity in Einstein's Train–Lightning Thought Experiment

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Abstract

Einstein's train–lightning thought experiment is commonly used to illustrate the relativity of simultaneity, yet many textbook treatments leave implicit a modeling choice: observers typically analyze the scenario as though their own inertial frame were at rest. This assumption is not required by the postulates of special relativity, which permit an observer to adopt any inertial frame as at rest and itself as moving relative to it. This paper develops an operational method that makes this choice explicit by treating the rest frame of the light sources as the reference for assigning propagation distances, with the sources understood as lightning in ground air or as bulbs fixed to the track. Working in the train frame, and using only the train's proper length, the relative velocity v, and the invariance of the speed of light c, the observer computes the propagation times and infers simultaneous emissions. The choice of source frame is an operational decision tied to the physical configuration of the emitters and does not introduce an absolute rest frame or imply any dependence of c on source or observer motion. The analysis does not replace the conventional interpretation but complements it by making explicit the operational choices involved in simultaneity judgments. Because the train–lightning experiment is almost universally presented as requiring the train observer to infer non-simultaneity, the analysis highlights how that conclusion depends on an implicit operational modeling choice while remaining consistent with special relativity. For completeness, Appendix A applies Selleri synchronization to Einstein's original thought experiment, illustrating how admissible synchronization conventions affect simultaneity assignments.

Keywords: operational simultaneity; relativity of simultaneity; Einstein train–lightning thought experiment; synchronization conventions; Selleri synchronization

1. Introduction

A previous article[1] introduced an operational method for determining simultaneity in Einstein's train–lightning scenario. The present paper develops that idea into a self-contained treatment suitable for this journal's audience: a derivation based solely on straight-line kinematics and the two postulates of special relativity. In the conventional presentation, Einstein's original reasoning implicitly assumes that each inertial observer regards their own frame as at rest when assigning propagation distances, which leads the train rider to infer non-simultaneity. This inference is widely taken to be unavoidable and is often identified directly with the relativity of simultaneity itself. The present paper argues that this appearance of inevitability arises from an implicit modeling assumption embedded in the standard presentation of the thought experiment. Because Einstein's train–lightning example has become one of the most widely reproduced illustrations of the relativity of simultaneity, clarifying the assumptions embedded in its standard presentation is of conceptual importance.

In contrast, the operational method assumes that the rest frame is the inertial frame of the light sources themselves, whether lightning or track-mounted bulbs, a modeling choice that any observer may adopt. Throughout this paper, the phrases *operational stance*, *operational analysis*, or *modeling choice of rest frame* all refer to this same approach, which is an explicit decision about which elements of the system are treated as at rest.

With the light sources taken as at rest in the operational method, the arrival-time asymmetry of light at the train midpoint arises entirely from the rider's motion relative to the sources. From this, the rider determines that the flashes were emitted simultaneously. This approach requires no synchronization of distant clocks and remains consistent with the two postulates of special relativity, including Einstein's synchronization convention.

For completeness, Appendix A applies Selleri synchronization to Einstein's original train–lightning thought experiment, showing that simultaneity can also arise under an alternative admissible synchronization convention, while the measured two-way light speed remains c.

2. Background: Einstein's two postulates and Einstein's thought experiment (concise recap)

Einstein's two postulates[2] state that (1) the laws of physics are the same in all inertial frames and (2) light in vacuum propagates at constant speed c, independent of the motion of the source or the observer.

In Einstein's thought experiment[3,4,5,6,7] a train moves at constant velocity v relative to the ground. Lightning strikes both the front and rear ends of the train simultaneously in the *ground frame* as the train's midpoint passes a platform observer who is at rest on the ground. A rider stands at the train's midpoint. **Figure 1** sketches the setup.

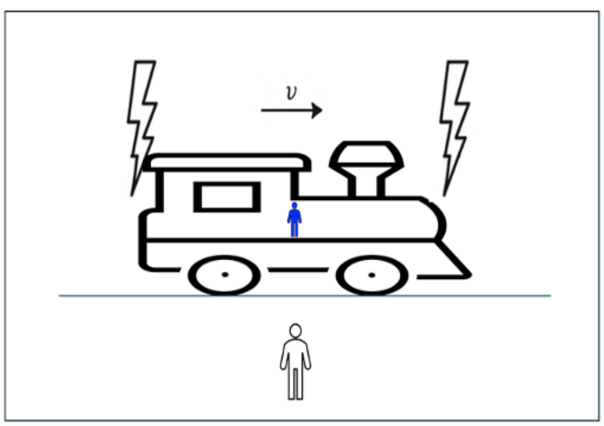

Figure 1: Schematic of Einstein's thought experiment in the ground frame: the train moves to the right at speed v relative to the ground; lightning strikes the ends as the midpoints coincide.

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Einstein's thought experiment is commonly presented as demonstrating that the two observers disagree about the simultaneity of the emissions. The ground observer sees the lights simultaneously but explains that the train rider will encounter the front flash before the rear flash because the rider moves toward the front and away from the rear while the light travels. Both observers agree on this *order of arrivals at the rider*. However, the train rider, who considers himself at rest, determines that the front flash occurred first because of the constant speed of light and the equal path lengths from the train's ends to its midpoint.

This reasoning is often left implicit in textbook summaries. The rider should not simply see the front flash first and declare the emissions non-simultaneous, as some presentations imply. Rather, the rider must also reason that because the flashes traveled equal distances, which are each half the train's length, to the midpoint at the same constant speed c, the front emission must have occurred earlier. The ground observer makes a corresponding inference using equal distances along the embankment. In both cases, the conclusion about simultaneity or non-simultaneity should not follow from visual perception alone but also from geometric reasoning based on equal path lengths and the constant speed of light in each observer's frame.

These conclusions are not forced by the two postulates of special relativity; rather, they depend on a particular modeling choice that each inertial observer regards their own frame as the one at rest when reasoning about simultaneity. Notably, this thought experiment does not rely on synchronized distant clocks for its conclusions.

As discussed in Jones & Childers, Contemporary College Physics[8], the synchronization of clocks is introduced before Einstein's train-lightning thought experiment to illustrate how local timekeeping is established within a single inertial frame. However, once the thought experiment itself is introduced, no distant clock readings are used. Both the ground observer and the train rider base their conclusions solely on the geometry of light propagation and the constancy of the speed of light. This is consistent with the literature, showing that Einstein's original setup remains standard in modern pedagogy.

In the next section, we discuss the operational method in the train frame by taking the light sources to be at rest in their own inertial frame during emission (here, the ground). This assignment reflects only the physical configuration of the emitters and chooses the rest frame of the light sources for light-travel accounting. If the sources were fixed to the train instead, the same reasoning would apply with roles reversed.

A familiar analogy[1] helps clarify this operational freedom: Consider a driver passing a stationary speed-limit sign. The driver may legitimately analyze their speed relative to the sign—treating the sign as stationary and themselves as moving. The sign provides a known physical reference. Likewise, in the train–lightning scenario, the rider may evaluate light-propagation relative to the light sources, which remain fixed in the ground frame during emission. Special relativity ensures identical physics in all inertial frames but does not require every observer to treat their own frame as stationary in every analysis. This same operational freedom underlies the method presented here.

3. The operational method (train frame only)

The operational method uses Einstein's thought experiment, *keeps the two postulates*, and *removes the common textbook choice* that each inertial observer must regard their own frame as at rest. The rider performs all reasoning in the train frame at the midpoint. The light sources (lightning or track-mounted bulbs) are treated as at rest in their own frame (the ground), a modeling choice about the sources and not a privileged-frame claim.[a] Two light emissions occur when ground-anchored sources pass the train ends. Under Einstein's setup, these emissions are simultaneous in the sources' rest frame (the ground). From the rider's perspective, the ground (and thus the emitters) move past at speed v, so the two flashes generally reach the midpoint at different times.

As Martin Gardner[9] emphasized, an inertial observer is not required to treat their own frame as the one at rest for analytical purposes and may instead adopt another inertial frame as stationary without violating either postulate of special relativity. This supports the operational stance taken here, where the light-source frame is used as the reference frame for assigning propagation distances.

Einstein's train-lightning thought experiment illustrates the relativity of simultaneity. Instead of relying on the implicit assumption that each inertial reference frame considers itself at rest, the operational method uses the same scenario while taking the rest frame of the light sources to be the one at rest. This operational choice is consistent with the two postulates of special relativity and leads any inertial observers, when they adopt this operational stance, to determine that the light emissions were simultaneous. The method is symmetrical in that the same form of reasoning applies if the light sources are instead fixed in a different inertial frame, such as the train frame.

The following analysis fully accounts for the arrival-time asymmetry of the lights by the rider's motion relative to the sources. All calculations below are carried out entirely in the train frame: the train retains its proper length L, light propagates at speed c, and the train moves at speed v relative to the ground-fixed emitters. Assigning the ground frame as the sources' rest frame reflects their physical configuration. Everything on the train moves with the train, and the train proper length L (its length in the train's rest frame) does not change for the rider just by considering the train to be moving.

Scenario: Emissions are simultaneous in the ground (light-source) frame, as in Einstein's original formulation.

Operational inputs (train-frame quantities):

- L: train's proper length (end-to-midpoint distance $L/2$).
- v: relative speed between train and ground.
- c: constant speed of light.
- $\Delta t_{arrival}$: the difference (rear minus front) between the two arrival times at the midpoint.

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[a] In the case of lightning, the discharge persists for a finite duration (typically milliseconds[1]) and appears sharply localized only in the frame in which the air is at rest. In Einstein's setup, this corresponds to the ground frame.

In the train frame, we derive the difference between the *arrival times of the rear and front flashes at the rider's midpoint*, which requires only straight-line kinematics and *c*.

Define flight-time intervals entirely in the train frame. Let t_{front} and t_{rear} be the light-flight time intervals between the *emission* at the front and rear ends of the train and the *arrival* of those flashes at the rider's midpoint, respectively. These intervals are quantities defined in the train frame and are either directly observed through the order of arrivals at the midpoint or calculated from geometry and the constant light-propagation speed c.

The following use the relations $distance = velocity \cdot time$.

- **Front flash.** At emission, the rider is a distance $L/2$ from the front end. During the time t_{front} until the light meets the rider, the light travels a distance ct_{front} toward the rider while the rider advances toward the front by vt_{front}. The meeting condition requires:

$$ct_{front} = (L/2) - vt_{front} \quad \Rightarrow \quad (c+v)t_{front} = L/2 \tag{1}$$

- **Rear flash.** At emission, the rider is a distance $L/2$ from the rear end. During the time t_{rear} until the light meets the rider, the light travels ct_{rear} toward the rider while the rider moves *away* from the rear by vt_{rear}. The light must travel:

$$ct_{rear} = (L/2) + vt_{rear} \quad \Rightarrow \quad (c-v)t_{rear} = L/2 \tag{2}$$

In these equations, the factors $c \pm v$ arise from a meeting condition and do not alter the light's invariant speed c.

Solving for the flight times for the two flashes to reach the train rider:

$$t_{front} = (L/2)/(c+v) \tag{3}$$

$$t_{rear} = (L/2)/(c-v) \tag{4}$$

The calculated travel-time difference between the two flight intervals to the rider is:

$$\Delta t_{travel} = t_{rear} - t_{front} = \left(\frac{L}{2}\right)\left(\frac{1}{(c-v)} - \frac{1}{(c+v)}\right) = \frac{Lv}{(c^2 - v^2)} \tag{5}$$

This operational method treats the situation as fully inertial, with no emission delays, accelerations, or other non-inertial effects.[1] All relevant quantities—length, time, velocity, and displacement—are defined entirely within the train rider's frame, and no quantities from any other inertial frame are introduced.

Because all quantities are defined in the train frame, the calculated travel-time difference must match the observed arrival-time difference of the flashes at the midpoint. Any difference in arrival times at the rider is entirely due to the different travel lengths of the flashes in the train frame; there is no other asymmetry in the system. Therefore, the observed arrival-time difference Δt_{obs} equals the calculated arrival-time difference Δt_{travel}:

$$\Delta t_{obs} = \Delta t_{travel} \tag{6}$$

Therefore, within this operational stance, the only consistent conclusion is that the light emissions were simultaneous:

$$\Delta t_{emission} = \Delta t_{obs} - \Delta t_{travel} = 0 \tag{7}$$

Recall that in Einstein's original thought experiment, the rider compares the difference in arrival intervals with the equal distances from the train ends in their own rest frame and concludes non-simultaneity of the emissions. The present operational method uses the same structure of reasoning: the observed difference in the flight-time intervals and the known train-frame distances determine the inferred emission-time relation.

Within this operational stance (light sources at rest in their inertial frame; rider and midpoint moving at speed v), the *arrival-time* asymmetry is fully accounted for by straight-line kinematics at speed c. Any residual difference must therefore be attributed to the emission times themselves.

4. Operational status within special relativity

The operational method introduced above remains within the standard framework of special relativity. All measured quantities used in the analysis, including distances, arrival-time differences, and relative velocities, are defined and evaluated entirely in the train frame.

Treating the light sources as being at rest in the ground frame reflects only the physical configuration of the emitters in Einstein's train–lightning thought experiment. Assigning a frame as "at rest" for the purpose of accounting for light propagation is an operational modeling choice that is equally admissible within special relativity, just as the conventional presentation treats each observer's own frame as at rest when assigning propagation distances.

Within this operational stance, the observed asymmetry in the arrival times of the two light flashes at the midpoint of the train is fully determined by kinematics at speed c. Once this is taken into account, no further kinematic contribution remains. Any such difference must therefore be attributed to an offset in the emission times themselves. The inference of simultaneity in this case follows directly from the operational assumptions adopted and does not rely on any modification of Einstein synchronization or the invariance of the speed of light.

This analysis clarifies that simultaneity judgments in Einstein's train–lightning thought experiment depend not only on the postulates of special relativity, but also on the operational modeling choice adopted for rest frames. Einstein's original reasoning implicitly adopts one such choice, while the present analysis adopts an alternative that is equally consistent with the theory. The inferred simultaneity depends on which admissible operational choice is adopted.

The operational result presented here relies only on Einstein synchronization. For completeness, Appendix A examines the same train–lightning scenario under Selleri synchronization, illustrating how admissible synchronization conventions affect simultaneity assignments while preserving the invariant two-way speed of light c. This supplementary analysis further clarifies the role of conventions in simultaneity judgments.

5. Conclusion

As in Einstein's train-lightning scenario, we take the emissions to be simultaneous in the rest frame of the light sources (here, the ground), consistent with the standard formulation of the thought experiment. The difference here arises from the operational stance, which takes the light-source frame as the one at rest, a modeling choice permitted within special relativity. Within this operational stance, the midpoint arrival-time asymmetry is determined entirely by train-frame geometry and light propagation at speed c; the rider must therefore conclude that the emissions were simultaneous. The analysis shows that the relativity of simultaneity in Einstein's train–lightning thought experiment depends essentially on operational modeling assumptions that are usually left implicit in standard presentations. For completeness, the appendix compares Einstein's and Selleri's synchronization conventions, showing that different conventions yield distinct simultaneity assignments without affecting the two-way speed of light c. This additional discussion offers readers a broader perspective on how both operational choices and conventions shape simultaneity judgments in special relativity.

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Appendix A: The Selleri convention shows simultaneity for the train frame

The conventional presentation of Einstein's train–lightning thought experiment illustrates the relativity of simultaneity using Einstein synchronization, which assumes isotropic one-way light speeds. Einstein noted that this assumption is a stipulation rather than an empirically determined fact. This appendix discusses Selleri's alternative synchronization convention for anisotropic one-way light speeds and applies it to Einstein's train–lightning thought experiment, illustrating how simultaneity assignments depend on the synchronization adopted.

Einstein's 1905 paper[2] established the theory of special relativity on two foundational postulates: (1) the laws of physics are the same in all inertial frames of reference, and (2) the speed of light in a vacuum is constant and equal to c for all inertial observers, regardless of the motion of the source or the observer. Einstein recognized that it was only possible to measure the two-way speed of light, c (now taken as $299{,}792{,}458\ m/s$), such as by reflecting a light from a mirror back to its source. He also introduced a synchronization convention whereby the one-way speed of light is equal to the average two-way speed of light, c. However, Einstein acknowledged that his one-way speed of light is a definition rather than an empirically verifiable fact.

This opens the door to alternative synchronization schemes. One notable proposal is that of Franco Selleri, who constructed a synchronization convention[10,11] which permits anisotropic one-way light speeds while preserving the constancy of the two-way speed of light. Under Selleri synchronization, if two events are simultaneous in one frame, they are simultaneous in all frames.

While Selleri's synchronization convention has been discussed in the literature, explicit applications to Einstein's train–lightning thought experiment are not standardly presented. The present appendix applies Selleri synchronization to this scenario and compares the resulting simultaneity assignments with those obtained using Einstein synchronization, thereby illustrating how admissible synchronization conventions influence simultaneity judgments.[[12]]

Recapitulation of Einstein's Train-Lightning Thought Experiment

Using Einstein synchronization, the one-way speed of light is assumed to be c in all directions.

Let the proper length of the train (its length in the train's rest frame) be L. Due to length contraction, the train's length in the ground frame is L/γ, and the distance from each end to the midpoint is $L/(2\gamma)$, where $\gamma = 1/\sqrt{1 - v^2/c^2}$ is the Lorentz factor. The Lorentz factor quantifies relativistic effects such as time dilation and length contraction.

To compute when the rider sees the flashes, we use the relation: distance = velocity × time.

Since the rider is located at the midpoint of the train, and the train is moving forward at velocity v in the ground frame, the rider is also moving forward relative to the flashes.

To find the time, t_F, for the front light to reach the moving midpoint (rider): $ct_F = \frac{L}{2\gamma} - vt_F \implies t_F = \frac{L}{2\gamma(c+v)}$.

To find the time, t_R, for the rear light to reach the moving midpoint (rider): $ct_R = \frac{L}{2\gamma} + vt_R \implies t_R = \frac{L}{2\gamma(c-v)}$.

Thus, $t_F < t_R$, so the rider sees the front flash first and, using Einstein synchronization, and determines that it occurred earlier. This illustrates the *relativity of simultaneity*.

Now, to calculate how these times appear in the train frame, we apply time dilation. Since the ground frame is moving at velocity relative to the train frame, the times observed in the train frame are:

$$t'_F = \frac{t_F}{\gamma} = \frac{L}{2\gamma^2(c+v)} \tag{A1}$$

$$t'_R = \frac{t_R}{\gamma} = \frac{L}{2\gamma^2(c-v)} \tag{A2}$$

These values, t'_F and t'_R, will be used in the next section when evaluating the emission times in the train frame using Selleri synchronization.

Einstein's synchronization convention, while elegant and widely adopted, relies on the stipulation of isotropic one-way light speeds—a definition rather than an empirical necessity. This raises the question: How would simultaneity and light propagation be interpreted under a different synchronization framework? Selleri's convention provides such an alternative, preserving simultaneity across frames by introducing anisotropic one-way light speeds while retaining the experimentally verified two-way speed of light. By applying Selleri's approach to the same train-lightning experiment, we illuminate how synchronization choices shape our interpretation of physical events.

Train Frame Analysis Using Selleri Synchronization (Ground Frame Preferred)

Selleri synchronization introduces anisotropic one-way light speeds, derived in Appendix B for completeness, in all frames except a designated preferred frame (here, the ground frame). This convention preserves simultaneity across frames while maintaining the experimentally verified two-way speed of light, c.

Now consider the same train-lightning thought experiment introduced earlier, but from the *train frame*, using *Selleri synchronization*, and where the *ground frame is considered the preferred frame*. In this framework, the ground frame uses isotropic one-way light speeds, while the train frame—being in motion relative to it—must adopt anisotropic one-way speeds. As a result, the train must calculate the timing of events by first applying time dilation to the times measured in the preferred frame.

From the previous section, we already determined the arrival times of the light flashes at the midpoint in the train frame (after applying time dilation):

$$t'_F = \frac{L}{2\gamma^2(c+v)} \quad \text{(arrival of front flash)} \tag{A3}$$

$$t'_R = \frac{L}{2\gamma^2(c-v)} \quad \text{(arrival of rear flash)} \tag{A4}$$

To determine when the flashes occurred in the train frame, the rider uses Selleri's anisotropic one-way light speeds. These are:

- From front to midpoint: $c_F = \gamma^2(c+v)$
- From rear to midpoint: $c_R = \gamma^2(c-v)$

The rider subtracts the time it would take light to travel from each end of the train to the midpoint (a distance $L/2$) using these speeds:

$$t'_{F\_emit} = t'_F - \frac{L/2}{\gamma^2(c+v)} \tag{A5}$$

$$t'_{R\_emit} = t'_R - \frac{L/2}{\gamma^2(c-v)} \tag{A6}$$

Substituting the expressions for t'_F and t'_R, then both emission times are equal to zero:

$$t'_{F\_emit} = t'_{R\_emit} = 0 \tag{A7}$$

This result shows that, according to Selleri synchronization in the train frame, the lightning flashes occurred *simultaneously*. Even though the rider sees the flashes at different times, the rider's calculations (based on Selleri's anisotropic one-way light speeds) show that the emission times were the same. This reinforces that simultaneity is a convention-dependent concept, and that using different synchronization schemes can yield consistent yet different accounts of when events occur.

Synchronization and Simultaneity

The analyses above show that simultaneity is not an empirically observed phenomenon but rather a consequence of the synchronization convention adopted. Under Einstein's synchronization, the assumption that the one-way speed of light is isotropic results in observers disagreeing about the simultaneity of distant events—a hallmark of special relativity. Selleri's synchronization, on the other hand, introduces anisotropic one-way light speeds in all frames except the designated preferred frame. This leads to the conclusion that distant events judged simultaneous in one frame remain simultaneous in all frames.

It is crucial to note that both synchronization conventions yield the same experimentally verifiable results for quantities such as the round-trip speed of light and time dilation. The key difference lies in the interpretation of when and where events occur. While Einstein synchronization emphasizes symmetry between inertial frames, Selleri's method introduces asymmetry through its designation of a preferred frame. This asymmetry is not in conflict with experimental results because the two-way speed of light remains c in all cases.

Contrasting Einstein's and Selleri's approaches highlights how synchronization conventions influence simultaneity assignments while preserving the invariant two-way speed of light.

Appendix B: Derivation of Selleri One-Way Light Speeds, and Confirmation of Two-Way Speed of Light c

This appendix is included for completeness and to make the paper fully self-contained. Selleri's synchronization assumes the existence of a preferred frame in which the one-way speed of light is isotropic and equal to c. For frames moving at velocity v relative to the preferred frame, the coordinate transformations are:

$$x' = \gamma(x - vt) \tag{A8}$$

$$t' = \frac{t}{\gamma} \tag{A9}$$

For a light ray traveling forward in the preferred frame (from the origin, $x = ct$):

$$x' = \gamma(ct - vt) = \gamma(c - v)t = \gamma^2(c - v)t' \tag{A10}$$

For a light ray traveling backward (from the origin, $x = -ct$):

$$x' = -\gamma(c + v)t = -\gamma^2(c + v)t' \tag{A11}$$

So, relative to the train frame, light has the coordinate velocities:

$$\frac{dx'}{dt'} = c_{forward} = \gamma^2(c - v) \text{ [travelling to the right]}$$
$$\frac{dx'}{dt'} = c_{backward} = -\gamma^2(c + v) \text{ [travelling to the left]} \tag{A12}$$

(A13)

To confirm that the two-way speed of light remains c, we will calculate the round-trip velocity of light going both ways over a distance of d' in the train frame.

In one direction the time of flight is:

$$t_1' = \frac{d'}{\gamma^2(c - v)} \tag{A14}$$

The travel time for the light reflected over the same distance is:

$$t_2' = \frac{d'}{\gamma^2(c + v)} \tag{A15}$$

The average speed for the round trip is (noting: $\gamma^2 = c^2/(c^2 - v^2)$:

$$\frac{2d'}{t_1' + t_2'} = c \tag{A16}$$

This ensures that Selleri synchronization remains compatible with all experimental evidence supporting the constancy of the two-way speed of light.

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