The Conventionality of Simultaneity and the Measurability of the One-Way Speed of Light

A Physical Constraint or a Philosophical Limitation?

René Oudeweg

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Abstract

The speed of light occupies a foundational role in modern physics, particularly in the structure of special relativity and the operational definition of spacetime. While the two-way (round-trip) speed of light is experimentally measurable with extraordinary precision, the one-way speed of light remains resistant to direct empirical determination. This paper examines whether this resistance reflects a merely philosophical limitation—arising from conventions of clock synchronization—or a deeper physical constraint imposed by the structure of spacetime itself. By analyzing the epistemic role of simultaneity, the operational content of measurement, and the invariance of physical laws under synchronization conventions, this paper argues that the unmeasurability of the one-way speed of light is best understood as a **structural feature of physical theory with philosophical implications**, rather than as a deficiency of experimental ingenuity.

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1. Introduction

Since the late nineteenth century, the speed of light has been recognized not merely as a parameter of electromagnetic phenomena, but as a fundamental constant shaping the geometry of spacetime. Experiments beginning with the work of **Albert A. Michelson** and **Edward W. Morley** demonstrated the invariance of the *round-trip* speed of light, providing the empirical impetus

for **Albert Einstein**'s formulation of special relativity. Yet a subtle and persistent question remains: *Can the one-way speed of light be measured independently of conventions?*
Despite over a century of technological advancement, no experiment has succeeded in measuring the one-way speed of light without presupposing a synchronization scheme that already embeds assumptions about that speed. This paper explores whether this limitation is contingent and philosophical, or whether it reflects a deeper physical constraint embedded in the operational structure of relativistic spacetime.

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2. Two-Way Versus One-Way Measurements: Operational Asymmetry

2.1 Two-Way Measurements

A two-way measurement of the speed of light involves a signal emitted from a source, reflected by a distant mirror, and received back at the source. The elapsed time is recorded using a single clock, eliminating the need for distant synchronization. All such experiments consistently yield a value of
m/sc=299,792,458 m/s,
a value now fixed by definition within the International System of Units.
Crucially, two-way measurements are **operationally closed**: they rely solely on local timekeeping and spatial distances, and therefore avoid any assumptions about simultaneity at a distance.

2.2 One-Way Measurements

By contrast, a one-way measurement requires:

1. A clock at the emission point,
2. A clock at the reception point,
3. A method for synchronizing these clocks.

The difficulty lies in step (3). Any synchronization procedure that uses light signals implicitly assumes something about the propagation speed of light itself. Thus, the measurement becomes circular: the one-way speed of light is required in order to define the very clocks used to measure it.

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3. The Conventionality of Simultaneity

Einstein proposed a synchronization convention whereby two distant clocks are said to be synchronized if light takes equal time to travel from A to B as from B to A. This convention renders the one-way speed of light isotropic and equal to the two-way speed.
Philosophers such as Hans Reichenbach later emphasized that alternative conventions are mathematically permissible. One may define synchronization such that light travels faster in one direction and slower in the opposite direction, provided the round-trip speed remains constant. These conventions are empirically indistinguishable, as all observable quantities depend solely on the two-way speed.
This leads to the thesis of the **conventionality of simultaneity**: simultaneity at a distance is not directly observable but defined by convention within a given theoretical framework.

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4. Is the Limitation Philosophical?

At first glance, the inability to measure the one-way speed of light appears philosophical rather than physical. After all:

- No known physical law forbids anisotropic one-way light speeds.
- Different synchronization conventions yield empirically equivalent descriptions.
- Observable predictions remain invariant under these conventions.

From this perspective, the limitation seems epistemic rather than ontological: nature may have a determinate one-way speed, but our knowledge of it is underdetermined by observation.
However, this conclusion risks underestimating the role of operational definitions in physics.

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5. The Physical Structure of Relativistic Spacetime

Special relativity does not merely *assume* a synchronization convention; it embeds synchronization into the definition of inertial frames and time coordinates. Within the theory:

- Time is not an independently measurable substance.
- Temporal ordering of spatially separated events depends on synchronization.
- Only causal structure (i.e., light cones) is invariant.

Crucially, no physical observable—no force, particle trajectory, or field interaction—depends on the one-way speed of light independently of synchronization. This is not an accident but a structural feature of the theory.
Thus, the unmeasurability of the one-way speed is not merely due to technological inadequacy or philosophical caution. It reflects the fact that **spacetime itself does not furnish an invariant notion of distant simultaneity**.

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6. Attempts to Circumvent the Limitation

Numerous proposals have sought to evade the synchronization problem using:

- Slow clock transport,
- Quantum entanglement,
- Accelerated reference frames,
- Cosmological anisotropies.

Yet all such methods either implicitly assume isotropic light propagation or reduce, upon careful analysis, to two-way measurements in disguise. To date, no proposal has produced an observable that depends uniquely on the one-way speed of light.

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7. Physical or Philosophical? A False Dichotomy

The question "Is this limitation philosophical or physical?" presupposes a distinction that may be too crude. The limitation is **physical in origin** but **philosophical in expression**.

- It is physical because it arises from the causal and geometric structure of spacetime.
- It is philosophical because it reveals the role of conventions in defining unobservable structures.
- It is methodological because it constrains what counts as a meaningful measurement.

In this sense, the unmeasurability of the one-way speed of light resembles gauge freedom in field theories: multiple mathematical descriptions correspond to the same physical reality, and no experiment can privilege one over another.

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8. Conclusion

The fact that only the two-way speed of light is directly measurable is not a mere accident of experimental history, nor a trivial semantic artifact. It is a profound consequence of how time, simultaneity, and causality are intertwined in relativistic physics.

The one-way speed of light cannot be measured without convention because **nature itself provides no operational handle on distant simultaneity**. This is not a failure of physics but one of its deepest insights: that some aspects of our theoretical descriptions are not dictated by empirical data alone, but by the frameworks through which that data becomes meaningful.

In this respect, the limitation is neither purely philosophical nor merely physical—it is a reflection of the boundary where physics and philosophy necessarily meet.