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A Physical Interpretation of the Law of Causality in Special Relativity and Its Philosophical Significance

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Abstract. Since Einstein proposed special relativity theory, physics has entered a new stage of development, providing a new analytical perspective for the problem of the law of causality. Based on the theoretical framework of special relativity, through the analysis of its development history, conclusions, and related thought experiments, this paper studies how it provides an anti-realist basis for the cognition of the law of causality and further helps to gain insight into the problem of causal circularity. By reviewing the development process of special relativity, this paper ultimately establishes the view that the essence of the empirical law of causality is a representation presented by the spacetime structure of the timelike interval region; that is to say, the objective spacetime structure is a necessary condition for the existence of the "law of causality" in a broad sense, rather than the traditional belief that the development of all science is based on the cognition of the law of causality. Subsequently, combined with the evolution of Russell's concept of causality based on this, this paper clarifies the core contradiction faced by the law of causality in philosophy in the contemporary era, namely the still unclear boundary between the empirical causality derived from the anti-realist conclusion of special relativity and the causality as pure logic indispensably used in the deductive process of special relativity.

Keywords: Special Relativity, Relativity of Simultaneity, Law of Causality, Russell, Causal Anti-realism

1. Introduction

After Einstein proposed the theory of special relativity, the concept of "relativity of simultaneity" instantly attracted widespread attention in the fields of physics and philosophy. Theory and experiments show that observers in different reference frames may make different judgments on the temporal order of events separated by a spacelike interval, whereas the temporal order of events separated by a timelike interval remains consistent in all reference frames. This discovery prompted people to re-examine the physical basis and applicable scope of causality and posed a challenge to the universal understanding of the traditional law of causality.Therefore, this paper attempts to make a new definition of the law of causality under the conceptual background of special relativity and to reflect on the realist position that "the law of causality is the premise of all scientific research." Specifically, this paper will first review the development history of the two basic postulates of special relativity, then clarify how the law of causality becomes the result of the spacetime structure

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defined by the timelike interval through a thought experiment, and finally conclude by reviewing the history of Russell's exploration of the essence of the law of causality based on special relativity. Overall, this paper deeply studies the essence of the law of causality based on special relativity; through the combination of physics and philosophy, it demonstrates the promoting role of special relativity in the discussion of the law of causality, how it provides support for causal anti-realism, and how it faces new difficulties in the problem of causal circularity. This study provides new references and prospects for how the development of natural science can contribute to future scientific philosophy research.

2. The Origin of the two basic postulates of special relativity

2.1. The principle of invariant light speed

Maxwell predicted in his electromagnetic equations that electromagnetic waves travel at the same constant speed c in a vacuum, which posed a problem for physicists holding the Galilean transformation system at that time: in which reference frame is this speed? They hypothesized that the medium preserving the energy during transmission was the ether, and the Earth moving in it would inevitably be affected by the "ether wind." However, in the Michelson-Morley experiment, the measured speed of light was equal when moving against and with the motion, with extremely small deviations, meaning no "ether wind" was detected, which severely weakened the rationality of the ether hypothesis. The physics community gradually tended to believe that the speed of light is the same constant c in all inertial reference frames. It can be found that the proposition of the principle of invariant light speed does not rely on the empirical law of causality [1, 2].

2.2. The principle of relativity

The Michelson-Morley experiment shows that light waves are not mechanical waves whose propagation relies on a material medium (such as ether), so their propagation speed does not depend on the state of the medium in the reference frame. Since the speed of light c is the rate at which all electromagnetic radiation propagates in a vacuum, the invariance of the speed of light implies that the formulation of electromagnetic laws has consistency in different inertial reference frames. The principle of relativity proposed by Galileo is not only a characteristic of mechanical phenomena but also applies to electromagnetic and optical phenomena. Thus, Einstein generalized the principle of relativity, and it also became another basic principle for the reasoning of special relativity.

3. Relativity of simultaneity: causality is no longer an a priori scientific premise

3.1. Definition of the law of causality

Russell critically examined three common definitions of the law of causality before proposing what he considered as the most precise version: Cause and effect are reciprocal concepts referring to any two distinct "things, phases, or aspects of reality that are so related that whenever the first ceases to exist, the second immediately begins to exist, and whenever the second begins to exist, the first has just ceased to exist." This definition highlights that the causality of two events depends on the chronological order of occurrence: the existence and cessation of the "first" and the "second" are separated by a minimal time interval. Therefore, a definite chronological order is one of the necessary prerequisites for two events to possess causality [3].

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3.2. Thought experiment: relativity of simultaneity disrupting temporal order disorder

In order to more intuitively demonstrate how the relativity of simultaneity causes observers in different reference frames to see the temporal order dislocation of events occurring at the same moment, leading to the failure of the law of causality, this paper designed a thought experiment.

Suppose there are three observers A, B, and C, initially located at the same position. A remains stationary, and the reference frame is the S frame. B moves to the right along the positive direction of the X-axis in space at a constant speed v = +0.6c, and the reference frame is the S' frame. At the same time, C moves to the left along the negative direction of the X-axis at a constant speed v = -0.6c, and the reference frame is the S'' frame. At t=0 in the S frame, event P and event Q (two flashes) occur simultaneously at x=0 and x=1 light-second, respectively. Therefore, from the perspective of the stationary observer A, events P and Q occur simultaneously at his moment of t=0, with no chronological order. However, for observers B and C, their time dilation factor is $\gamma=\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}=\frac{1}{\sqrt{1-0.6^2}}=1.25$. According to the Lorentz transformation:

$$t'=\gamma\left(t-\frac{v}{c^2}x\right),\ x'=\gamma\left(x-vt\right) \tag{1}$$

Therefore, in the S' frame where B is located, event P occurs at $t'_P=1.25\left(0-\frac{0.6c}{c^2}\times 0\right)=1.25\times 0=0$, and event Q occurs at $t'_Q=1.25\left(0-\frac{0.6c}{c^2}\times c\times 1\right)=1.25\times(-0.6)=-0.75$ seconds. In the S'' frame where C is located, event P occurs at $t''_P=1.25\left(0-\frac{(-0.6c)}{c^2}\times 0\right)=1.25\times 0=0$, and event Q occurs at $t''_Q=1.25\left(0-\frac{(-0.6c)}{c^2}\times c\times 1\right)=1.25\times 0.6=0.75$ seconds [4].

It can be seen that in A's reference frame, events P and Q occur simultaneously; in B's reference frame, P occurs 0.75 seconds later than Q; in C's reference frame, P occurs 0.75 seconds earlier than Q. Therefore, "simultaneity" is relative to the reference frame, and the chronological order of events perceived by the observer also depends on the reference frame they are in.

3.3. Timelike interval and spacelike interval

Does the above discovery mean that the law of causality has been completely dismantled? In fact, the law of causality only fails as shown in the thought experiment under a specific spacetime structure, that is, when two events have a spacelike interval. The spacetime interval is a geometric quantity describing the invariant relationship between events in a four-dimensional spacetime coordinate system, and its definition is:

$$\Delta s^2=(c\Delta t)^2-(\Delta x)^2 \tag{2}$$

When $\Delta s^2 > 0$, the two events are separated by a timelike interval, and the events are distributed inside the light cone, namely, the blue area in Figure 1. This indicates that points in the future light cone can affect the origin event through subluminal motion, while points in the past light cone can be affected by the origin event through subluminal action. Timelike interval events, such as point A, can maintain an absolute chronological order in any inertial reference frame. When $\Delta s^2 < 0$, the two events are separated by a spacelike interval. Such events are distributed outside the light cone, such as point B. This means that the spatial distance Δx between the two events exceeds the distance $c\Delta t$

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that light can travel in the specified time. And since the speed of light is the maximum speed for signal propagation, these two events cannot be connected by any signal, nor is it possible to establish a causal connection [5-7].

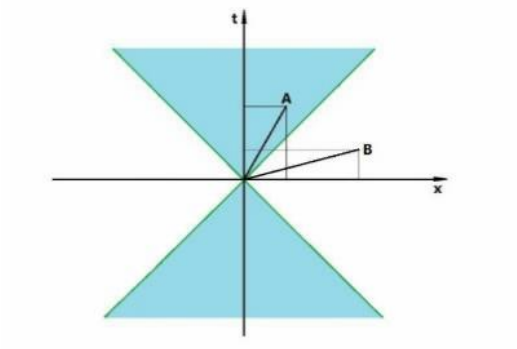

Figure 1. Schematic diagram of a light cone

In the thought experiment above, the spacetime interval between P and Q is $\Delta s^2=(c\times 0)^2-(1\times c)^2=-(1\times c)^2<0$, which is exactly a spacelike interval. Therefore, the temporal order of P and Q is relative.

4. Special relativity's support for causal anti-realism and unresolvable philosophical difficulties

4.1. Spacetime structure determines the existence of the law of causality

Therefore, when two events have a timelike interval, a causal relationship can be established; whereas when the spatial distance between two events is too large and they have a spacelike interval, the law of causality does not exist. This is because the maximum speed of signal propagation is limited by the speed of light. If no signal connects the two events, their temporal order cannot be consistent across all reference frames. According to Russell's definition of the law of causality, there can be no causal relationship between the two.

This does not mean that the state of events separated by a spacelike interval cannot be described in physical language: the time and spatial positions of events P and Q in different reference frames can both be calculated in a four-dimensional spacetime coordinate system starting from the two basic postulates of special relativity. From this, it can be found that the existence of the law of causality is not a prerequisite for scientific operation; on the contrary, it is exactly the objective spacetime structure deduced by calculations in physics that determines the existence of the law of causality. This weakens the causal realist view that causal connections inevitably exist.

Let us recall the sources of the two basic postulates of special relativity. The proposition of the principle of invariant light speed originated from the theoretical prediction in Maxwell's equations that the speed of electromagnetic waves is a constant c. This result created tension with the relativity of velocity under the Galilean transformation system; later, the Michelson-Morley experiment showed that measuring the speed of light in different directions did not produce significant differences. This result weakened the "ether" hypothesis and also shook the traditional concept that the speed of light would superimpose the speed of the reference frame. Therefore, Einstein made an intuitive inference: the speed of light in a vacuum is independent of the reference frame in which it is measured. This postulate actually does not have a physical "cause". Einstein's principle of

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relativity is an extension of Galileo's principle of relativity. Galileo's principle of relativity is an intuitive induction of all mechanical phenomena and is one of the basic principles of physics, and it also has no "cause." Einstein's extension of it to all inertial reference frames is a conceptual expansion proposed based on further thinking about the principle of invariant light speed. It can be said that these two postulates are at the forefront of the evolutionary chain of physical laws, belong to the premises that define the law of causality, and cannot be deduced by causal logic.

However, as two hypotheses, the process of their discovery still follows the causal chain of human thinking: either arising from further inferences about experimental facts or based on thinking about contradictory premises in two theoretical systems.

But the two postulates cannot be called empirical conclusions. According to Einstein's exposition, they belong to the "free inventions of the human mind" and are not products derived from experience through logical deduction. Absolute hypotheses cannot be drawn from limited empirical induction; their sources are closer to a creative, ideational invention from nothing. Ideational causality, that is, causal logic and mathematical language, is also the source of the rational intuition of "free inventions," and it is not limited by the law of causality under a spacetime background. It belongs to an epistemological tool, a carrier of thought rather than its result; whereas the law of causality in the empirical world is the result of a specific spacetime structure.

4.2. Russell's judgment on the law of causality

When reflecting on the law of causality, Russell noted that there is a certain circularity problem in scientific research: there is a certain circularity when constructing with the concept of causality, and causality itself is exactly defined within these constructions. In the context of special relativity, science proposes a new definition of the law of causality based on whether signals can be perceived, which also demonstrates the inevitability of this circular definition problem. Russell initially viewed causal logic as a form of the law of causality itself but later had to attempt to distinguish them. After multiple considerations and judgments, he shifted from causal anti-realism to neutral monism and made an exhaustive discussion on the application scope and foundation of the two concepts of causality.

Initially, in his 1912 paper "On the Notion of Cause," Russell classified the law of causality as a "relic of a bygone age." The reason is exactly as revealed by the computability of spacelike interval regions: in science, "causality" is not the premise of everything, but functions (differential equations) are. Holding causal anti-realism, he believed that the world is composed of particulars and universals, and the task of science is precisely to discover the functional relationships between these particulars. The necessity and coerciveness of "causality" are one-sided and harmful. At this time, because he confused the empirical world's law of causality and causal logic, blending their definitions together, he believed that the binary relationship of causality in the empirical world would lead to the logical dilemma that cause and effect must be absolutely continuous in time. His proposed "substitution of functional relations for the law of causality" was exactly another expression of causal logic; that is, Russell's first solution to the circular definition dilemma had actually implicitly distinguished causal logic and the law of causality. However, he believed that their objects were still the same and the relationship between them was iterative, so he advocated abandoning all uses of the law of causality.

However, in "The Analysis of Matter" in 1927, Russell realized that the construction of the physical world cannot be divorced from the law of causality, so he proposed the causal line theory based on his definition of the law of causality, taking point-instants and particles (electrons) as particulars: an object is a causal line composed of a series of events that are temporally continuous

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and similar to each other. The causal line theory is Russell's new modification of the law of causality in the empirical world, but the process abstracted from the event sequence relies on the law of causality in the transitional zone between logic and experience, making the circularity problem once again unavoidable. In other words, at this point, Russell discovered that logical and empirical laws of causality are no longer two mutually exclusive expressions with the same object. He distinguished their objects but found that their objects have compatibility in certain situations and cannot be independently explained by one theory. That is, many inferences in science (such as inferring external objects from perception) go beyond direct observation, raising the question of what form of the law of causality provides the foundation for such inferences. Therefore, Russell attempted to distinguish the physical and the mental, trying to propose a new solution to Hume's problem of induction [8].

In 1948, in "Human Knowledge: Its Scope and Limits," Russell gave his final response to this problem. He proposed five postulate premises under which causal theories, including the causal line theory, could be absolutely established in the empirical world and indicated: although these postulates cannot be proven true, if they are not established, any empirical knowledge would be impossible. At this point, Russell suspended his speculation on the reality of the law of causality by compromising with Hume's problem and made a neutral monist claim on the mind-body problem: he had always attempted to unify the physical and mental laws of causality. Although the causal line theory failed to provide a perfect response, it remains an endeavor within their power by neutral monists regarding the causal circularity problem [9, 10].

5. Conclusion

This paper first reviewed the discovery process of special relativity and pointed out that the proposition of its two basic postulates did not involve empirical (physical) laws of causality, and the subsequent specific conclusions were merely the result of mathematical deduction. Then, through a thought experiment where three observers in different spatial positions observed different temporal orders of the same two events, it revealed the relativity of temporal order in spacelike interval regions. This deconstructed the concept that people consider the law of causality to have absoluteness and showed that the empirical law of causality is just the result of a specific physical spacetime structure. Finally, based on special relativity, by reviewing the intellectual history of Russell on the law of causality, we can gain deeper insight into the existential essence of the law of causality in both physical and mental aspects. According to the conclusion of special relativity, the existence of the physical law of causality depends on the objective spacetime structure, and its essence is merely a representation of a "functional relationship," whereas the mental law of causality, as an indispensable cornerstone for the discovery of special relativity and all mathematical derivations, its existence cannot be questioned. Russell attempted to unify the two from the perspective of neutral monism and proposed five indispensable hypotheses for unification as his final conclusion.

Before the discovery of special relativity, the discussion of the law of causality and the mind-body problem in philosophy had always been like blind men feeling an elephant; however, discoveries in physics subverted people's cognition that "the law of causality is the cornerstone of all natural sciences" and showed that the essence of the so-called empirical law of causality needs to depend on the existence of physical structures, which also provides new ideas for philosophical discussion. Hereby, researchers cannot help but imagine whether new discoveries in future physics can provide new inspirations and solutions to the problem of causal circularity.

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