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Phase Structure and the Lightlike Boundary

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Abstract

This paper develops a minimal structural framework connecting relativistic and quantum descriptions through a shared lightlike boundary. Rather than introducing new dynamics, the aim is to identify a small set of relations that organize familiar features of physics in a unified way.

Starting from the observation that distinct physical regimes converge to a common invariant limit, we define a boundary parameter and corresponding phase structure. These are used to reinterpret relativistic relations, the Lorentz factor, and the role of phase in quantum mechanics. The results are structural and interpretive, providing a foundation for further development.

1 The Starting Point

The present framework begins with the observation that distinct physical descriptions exhibit a common limiting structure.

From relativistic mechanics, the energy–momentum relation is [3, 4]:

$$E^2 = p^2c^2 + m^2c^4. \tag{1}$$

In the limit $m \to 0$, this reduces to:

$$E = pc, \tag{2}$$

so that:

$$\frac{E}{p} \to c. \tag{3}$$

From wave and quantum considerations [1, 2], the phase may be written as:

$$\Phi = px - Et, \tag{4}$$

with:

$$p_i = \partial_i \Phi. \tag{5}$$

The phase velocity is:

$$v_p = \frac{\omega}{k} = \frac{E}{p}. \tag{6}$$

The group velocity is:

$$v_g = \frac{d\omega}{dk}. \tag{7}$$

For relativistic dispersion, this becomes:

$$v_g = \frac{pc^2}{E}. \tag{8}$$

Thus, in the massless limit:

$$v_p \to c \tag{9}$$

and

$$v_g \to c. \tag{10}$$

Both descriptions therefore converge to the same invariant null structure.

This may be expressed covariantly as:

$$d\sigma^2 = 0, \tag{11}$$

or equivalently for the phase field:

$$\partial_i \Phi \, \partial^i \Phi = 0. \tag{12}$$

The central idea is that distinct physical descriptions are unified not by direct equivalence, but by coincidence of their limiting behavior at a shared lightlike boundary.

2 Introduction

In *UNIFICATION*, we showed that relativistic and quantum descriptions meet at a shared lightlike boundary.

On the relativistic side, the massless condition is:

$$E = pc. \tag{13}$$

On the quantum side, using the standard relations [1, 2]:

$$E = \hbar\omega, \qquad p = \hbar k, \tag{14}$$

the same boundary yields:

$$\omega = ck. \tag{15}$$

Thus, the relativistic and quantum descriptions coincide at the same invariant lightlike limit.

Motivated by this shared limiting structure, we define the boundary parameter:

$$\chi = \frac{v}{c} = \frac{pc}{E} = \frac{kc}{\omega}. \tag{16}$$

This parameter measures proximity to the lightlike boundary defined by the invariant speed c. We also define the corresponding deviation from the boundary:

$$\delta = 1 - \chi^2. \tag{17}$$

The purpose of the present paper is to explore the consequences of this structure and to develop a phase-based interpretation consistent with both relativistic and quantum descriptions.

Guiding Principle

The guiding idea of the present framework is that distinct physical descriptions may be unified not by direct equivalence, but by coincidence of their limiting behavior at a shared invariant boundary.

In this sense, the lightlike condition defines an organizing structure from which both relativistic and quantum features may be interpreted as emerging.

3 Phase Structure

We now introduce a phase ratio intended to compare externally expressed phase propagation with internally associated phase structure:

$$\chi_\phi = \frac{\omega_{\text{ext}}}{\omega_{\text{int}}}. \tag{18}$$

A natural identification is obtained from relativistic energy relations [3, 4].

The external phase frequency may be associated with the total energy:

$$\omega_{\text{ext}} = \frac{E}{\hbar}, \tag{19}$$

while the internal phase frequency may be associated with rest energy:

$$\omega_{\text{int}} = \frac{mc^2}{\hbar}. \tag{20}$$

Thus:

$$\chi_\phi = \frac{E/\hbar}{mc^2/\hbar} = \frac{E}{mc^2}. \tag{21}$$

Using:

$$E = \gamma mc^2, \tag{22}$$

we obtain:

$$\boxed{\chi_\phi = \gamma}. \tag{23}$$

Since:

$$\gamma = \frac{1}{\sqrt{1-\chi^2}}, \tag{24}$$

it follows that:

$$\boxed{\chi_\phi = \frac{1}{\sqrt{1-\chi^2}}}. \tag{25}$$

This identification suggests that the amplification of external phase relative to internal phase is determined by proximity to the lightlike boundary.

As:

$$\chi \to 1, \tag{26}$$

we have:

$$\chi_\phi \to \infty. \tag{27}$$

Thus, as the lightlike boundary is approached, externally expressed phase propagation increasingly dominates over internal phase evolution.

This interpretation is consistent with the broader idea that both relativistic and quantum descriptions may be governed by a shared phase structure whose limiting behavior is determined by the invariant boundary.

4 Boundary Behavior

The framework organizes several limiting behaviors through the single boundary parameter χ.

As:

$$\chi \to 1, \tag{28}$$

the deviation parameter tends to zero:

$$\delta \to 0. \tag{29}$$

Since:

$$\gamma = \frac{1}{\sqrt{\delta}}, \tag{30}$$

the Lorentz factor diverges:

$$\gamma \to \infty. \tag{31}$$

Likewise, from the phase ratio relation:

$$\chi_\phi = \frac{1}{\sqrt{1-\chi^2}}, \tag{32}$$

we obtain:

$$\chi_\phi \to \infty. \tag{33}$$

Thus, the limiting behavior may be summarized as:

$$\chi \to 1, \qquad \delta \to 0, \qquad \gamma \to \infty, \qquad \chi_\phi \to \infty. \tag{34}$$

These limits are not independent, but arise from the same invariant boundary structure.

Proper Time at the Boundary

Proper time is given by [5]:

$$d\tau = dt\sqrt{1 - \chi^2} = dt\sqrt{\delta}. \tag{35}$$

Using the phase ratio:

$$d\tau = \frac{dt}{\chi_\phi}. \tag{36}$$

Thus, as:

$$\chi \to 1, \tag{37}$$

we obtain:

$$d\tau \to 0. \tag{38}$$

This suggests that proper time may be interpreted as internal phase evolution, while coordinate time reflects external propagation.

As external phase propagation becomes dominant relative to internal phase evolution, the rate of internal temporal progression decreases.

Approach to the Boundary

The relativistic energy relation is:

$$E^2 = (pc)^2 + (mc^2)^2. \tag{39}$$

For a massless system:

$$m = 0 \quad \Rightarrow \quad E = pc. \tag{40}$$

This describes exact lightlike propagation.

For a massive system:

$$E = \gamma mc^2. \tag{41}$$

As:

$$v \to c, \tag{42}$$

the Lorentz factor diverges:

$$\gamma \to \infty, \tag{43}$$

and therefore:

$$E \to \infty. \tag{44}$$

Thus, two distinct limiting processes approach the same boundary:

- $m \to 0$, corresponding to intrinsically lightlike systems;
- $v \to c$ with $m \neq 0$, requiring unbounded energy.

Both converge to the same invariant lightlike condition.

Interpretation

The lightlike boundary is therefore associated simultaneously with:

- vanishing deviation ($\delta \to 0$),
- vanishing proper time ($d\tau \to 0$),
- diverging Lorentz factor ($\gamma \to \infty$),
- diverging phase ratio ($\chi_\phi \to \infty$).

In this sense, zero-like and infinity-like behaviors appear as complementary aspects of the same invariant boundary defined by the speed of light c.

This perspective does not assign literal numerical meaning to zero or infinity, but treats them as limits arising from invariant spacetime structure.

5 Conclusion

We have introduced a minimal structural framework based on a shared lightlike boundary and a corresponding phase structure.

The central idea is that distinct physical descriptions converge to the same invariant limit, and that this limit may organize both relativistic and quantum features.

The principal boundary relation is:

$$E = pc \qquad \Leftrightarrow \qquad \omega = ck. \tag{45}$$

This motivates the definition of the boundary parameter:

$$\chi = \frac{v}{c} = \frac{pc}{E} = \frac{kc}{\omega}. \tag{46}$$

From this follows the deviation parameter:

$$\delta = 1 - \chi^2, \tag{47}$$

which organizes several familiar relativistic quantities.

In particular:

$$\gamma = \frac{1}{\sqrt{\delta}}, \tag{48}$$

and:

$$d\tau = dt\sqrt{\delta}. \tag{49}$$

The introduction of the phase ratio:

$$\chi_\phi = \frac{\omega_{\text{ext}}}{\omega_{\text{int}}} = \gamma \tag{50}$$

provides an interpretive connection between relativistic time dilation and phase evolution.

As the lightlike boundary is approached:

$$\chi \to 1, \tag{51}$$

we find:

$$\delta \to 0, \qquad \gamma \to \infty, \qquad \chi_\phi \to \infty, \qquad d\tau \to 0. \tag{52}$$

Thus, zero-like and infinity-like limiting behaviors may be understood as complementary aspects of a shared invariant boundary.

The present work remains interpretive rather than dynamical.

No new equations of motion are introduced, and no modification of established relativistic or quantum theory is claimed.

Rather, the contribution of this paper is structural:

it suggests that a small set of relations may provide a common organizational basis for familiar physical phenomena.

In particular, mass may be interpreted as deviation from the lightlike boundary, and proper time may be interpreted as internal phase evolution.

Whether this structural insight can be extended into a full dynamical theory remains a question for future work.

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