The Causal Budget and Transformation Laws: Proper Time As Emergent

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Abstract

This paper proposes a physically grounded, system–centric definition of time. *Proper Time* is redefined as the duration of a system's physical transformation as energy overcomes resistance. This intrinsic interval arises from a conserved causal capacity partitioned between internal transformation rate and external motion.

A system experiences time only to the extent that it undergoes physical change, while massless systems, lacking internal transformation, experience none. Time is thus interpreted as a localized, emergent, and relational property of causal structure rather than an external backdrop, consistent with both relativistic invariance and thermodynamic irreversibility.

In this system–centric formulation, durations and rates are defined from each system's own physical perspective, emphasizing that causal suppression is an objective physical effect rather than a matter of observational standpoint.

Keywords: time, proper time, causal structure, physical transformation, relational ontology, emergence of time

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1. Introduction

The nature of time remains one of the most enduring problems in physics and philosophy [12]. Classical physics treated time as an absolute backdrop [1], relativity reinterpreted it as a coordinate within spacetime geometry [3, 2], and thermodynamics associated its arrow with entropy production [4, 6]. Yet all these frameworks leave open the fundamental question: *what is time physically?*

Here we take a system–centric view. Time is not an external parameter but a measurable consequence of physical transformation itself. It exists only insofar as energy is applied and irreversibly processed through resistance. When a system drives energy E through its intrinsic opposition at finite throughput P, it advances its own internal state by one causal tick of duration $\tau = E/P$. The accumulation of such ticks constitutes the system's proper time.

In this picture, every system evolves according to a finite causal budget that can be distributed between external motion and internal transformation. Thus, time arises as a manifestation of physical change, not as a geometric dimension or observer-dependent coordinate.

2. Causal Transformation and Proper Time

Postulate (Causal Transformation Extent). A system transformation is composed of discrete quantum processes, or causal ticks. Each tick corresponds to an energy input E applied at power P, driving an intrinsic transformation at speed v_{int}, and producing a transformation extent $\mathcal{T}$ (dimension: length):

$$\mathcal{T} = \frac{E v_{\text{int}}}{P}. \tag{1}$$

Here E is the irreducible energy associated with one completed transformation, P is the throughput (power) driving that transformation, and v_{int} represents the system's *causal throughput rate* — the rate at which it converts between spatial and temporal aspects of internal transformations. It characterizes how the system allocates causal capacity, not the literal velocity of internal components.

When $v_{\text{int}} = c$ for a radiative process, this indicates saturation of the causal throughput limit, empirically manifested as the universal relation $\ell_{\text{causal}} f = c$ between spatial stride and tick frequency. Comprehensive evidence across atomic, optical, and astrophysical systems shows c emerges as the ratio of spatial stride per causal tick to proper-time duration per tick (Sec. 4). Units: E [J], P [J/s], v_{int} [m/s], hence $\mathcal{T}$ [m].

Proper Time from Transformation Extent. The proper-time duration of one causal tick is defined as the transformation extent divided by the universal causal speed:

$$\tau = \frac{\mathcal{T}}{c}. \tag{2}$$

This τ represents the intrinsic tick duration measured when the system is at rest relative to its causal frame.

Examples.

- **Quantum:** A discrete transition (e.g., spin flip, atomic hyperfine transition). The energy E is the transition energy. At rest, $v_{\text{int}} = c$ yields $\mathcal{T} = \lambda$, giving $\tau = \lambda/c = 1/\nu$.

- **Classical:** A reproducible cycle (e.g., mechanical oscillation). Here E is the energy processed per cycle and $\tau_0 = E/P$ gives the rest-frame period.

2.0.1. Intrinsic Transformation Speed and Causal Budget

Causal Budget Constraint. A system shares its total causal capacity between external motion and internal transformation (5):

$$v_{\text{ext}}^2 + v_{\text{int}}^2 = c^2.$$

Thus,

$$v_{\text{int}} = \sqrt{c^2 - v_{\text{ext}}^2}. \tag{3}$$

2.0.2. Tick Duration Under Motion

Substituting Eq. (3) into (1) and (2) gives the tick duration for a moving system:

$$\tau = \frac{E\sqrt{c^2 - v_{\text{ext}}^2}}{Pc} = \frac{E}{P}\sqrt{1 - \frac{v_{\text{ext}}^2}{c^2}}. \tag{4}$$

Interpretation: When $v_{\text{ext}} > 0$, the system allocates part of its causal budget to external motion, reducing v_{int} and thus lengthening the tick duration τ as measured by its internal processes. The rest-frame tick duration $\tau_0 = E/P$ is the minimal achievable value.

Empirical Identification. For radiative processes, the transformation extent $\mathcal{T}$ equals the emitted wavelength λ when $v_{\text{int}} = c$, yielding $\tau = \lambda/c$ (e.g., the Cs-133 hyperfine transition). This provides operational meaning to $\mathcal{T}$.

The causal budget framework not only predicts ideal clock behavior but also naturally accounts for real-world frequency uncertainties, as shown next.

Frequency stability from causal-budget fluctuations. Consider small perturbations of the external velocity about a mean,

$$v_{\text{ext}} = \bar{v}_{\text{ext}} + \delta v, \qquad |\delta v| \ll c,$$

with $\tau(v) = \tau_0\sqrt{1 - v^2/c^2}$ and $\tau_0 = E/P$. A Taylor expansion about $v = \bar{v}_{\text{ext}}$ to second order gives

$$\tau(\bar{v}_{\text{ext}} + \delta v) \approx \tau(\bar{v}_{\text{ext}}) - \frac{\tau_0\,\bar{v}_{\text{ext}}}{c^2\sqrt{1 - \bar{v}_{\text{ext}}^2/c^2}}\,\delta v - \frac{\tau_0}{2c^2}\left(1 - \frac{\bar{v}_{\text{ext}}^2}{c^2}\right)^{-3/2}\delta v^2.$$

The fractional frequency fluctuation $f = 1/\tau$ is, to leading order,

$$\frac{\delta f}{f} \approx -\frac{\delta\tau}{\tau} \approx \frac{\bar{v}_{\mathrm{ext}}}{c^2\big(1 - \bar{v}_{\mathrm{ext}}^2/c^2\big)}\,\delta v + \mathcal{O}(\delta v^2).$$

Assuming unbiased fluctuations $\langle \delta v \rangle = 0$, the variance of the fractional frequency is

$$\mathrm{Var}\!\left(\frac{\delta f}{f}\right) \approx \frac{\bar{v}_{\mathrm{ext}}^2}{c^4\big(1 - \bar{v}_{\mathrm{ext}}^2/c^2\big)^2}\,\sigma_v^2,$$

where $\sigma_v^2 = \langle \delta v^2 \rangle$.

In the nonrelativistic limit $\bar{v}_{\mathrm{ext}} \ll c$ this reduces to

$$\frac{\sigma_f}{f} \approx \frac{\bar{v}_{\mathrm{ext}}}{c^2}\,\sigma_v,$$

which reproduces the characteristic scaling of second-order Doppler broadening observed in precision clocks [13]: velocity fluctuations map into frequency noise because time dilation depends sensitively on velocity when the mean drift is nonzero.

Remarks: the expansion assumes $|\delta v| \ll c$ and that higher-order terms are negligible for the noise level considered.

These fluctuations represent the stochastic, real-world manifestation of the same causal–budget principle introduced in Section 4.1, where the ideal deterministic bounds [13, 16, 15, 14] emerge as the limiting cases of the relation $f = P/E$.

3. The Causal Budget Law

3.1. Postulate and empirical basis

All physical systems continuously evolve. We posit that each system has access to a single finite causal capacity c, which can be allocated in two ways: (i) to translate the system through space, and (ii) to advance the system's own physical state.

We represent that allocation with the causal budget law

$$c^2 \;=\; v_{\mathrm{ext}}^2 + v_{\mathrm{int}}^2, \tag{5}$$

where v_{ext} is the system's bulk spatial speed, and v_{int} is the system's internal transformation rate. By "intrinsic transformation rate" we mean: the spatially-calibrated rate at which the system physically re-specifies itself — i.e., the rate at which energy is driven through its own internal opposition channel to produce an actual transformation (spin/polarization flip, field reconfiguration, stress-pattern update, biochemical advance, etc.). Both $v_{\rm ext}$ and $v_{\rm int}$ carry units of m/s.

Crucially, $v_{\rm int}$ is not "internal jiggle" or some private, hidden sub-motion. It is the causal rate at which the system as a whole becomes its next physical self. $v_{\rm ext}$ measures how fast that self moves through space. $v_{\rm int}$ measures how fast that self is being advanced.

Equation (5) therefore encodes a single finite resource. At $v_{\rm ext} = 0$, none of that capacity is assigned to translation, so the full capacity is available to drive intrinsic transformation and $v_{\rm int} = c$. In the lightlike limit $v_{\rm ext} \to c$, all capacity is assigned to translation, and intrinsic transformation stalls: $v_{\rm int} \to 0$.

Massive systems necessarily satisfy $v_{\rm int} > 0$, so they cannot reach $v_{\rm ext} = c$. Only systems whose physical state does not continue to update (effectively $v_{\rm int} = 0$) can saturate $v_{\rm ext} = c$.

Empirical foundation. We are *not* introducing a new constant. The same c already appears as the empirically invariant two-way signal speed used to define the SI meter and second. Here it is promoted to a universal *causal capacity*: the maximum rate at which any physical system can advance either through external displacement or intrinsic transformation.

This is consistent with familiar operational identities that already treat c as a conversion between energy flow, momentum flow, and force: radiation pressure satisfies $F = P/c$, relativistic mass–energy satisfies $E = \Delta m\, c^2$, and energy/momentum fluxes are linked by S/c^2 in electromagnetic stress-energy flow. These relations are routinely confirmed in experiment and engineering; they all encode the same finite, invariant c [17].

In this framework, Eq. (5) is therefore not an added spacetime postulate. It is a conservation statement: total causal processing capacity c is finite and invariant, and any use of that capacity for bulk motion leaves less available for internal evolution, and vice versa.

3.2. Derivation from first principles

The causal budget law can be derived from three fundamental principles:

1. **Conservation.** Every physical system has a fixed total causal capacity c; this total does not change during motion or interaction.
2. **Independence.** External translation ($v_{\rm ext}$) and intrinsic transformation ($v_{\rm int}$) are distinct channels of causal activity. Spending more on one does not directly *become* the other, but both draw from the same pool.
3. **Boundary conditions.** A system that is not translating at all ($v_{\rm ext} = 0$) must still be able to internally evolve, so $v_{\rm int} = c$. A system pushed to its limiting translational rate ($v_{\rm ext} = c$) cannot evolve internally any further in its own state while maintaining that propagation, so $v_{\rm int} = 0$.

We now ask: what continuous relation between v_{ext} and v_{int} satisfies (i) conservation of a single invariant total capacity, (ii) independence of the two channels, and (iii) the boundary conditions $(v_{\text{ext}}, v_{\text{int}}) = (0, c)$ and $(c, 0)$?

The unique smooth, symmetric way to do this is to treat v_{ext} and v_{int} as orthogonal components of a single conserved "causal capacity vector" of fixed magnitude c. That prescription gives the Pythagorean form

$$c^2 = v_{\text{ext}}^2 + v_{\text{int}}^2, \tag{6}$$

which is exactly Eq. (5).

This is not an assumption of spacetime geometry. The point is that if you want (i) a single invariant scalar capacity c, (ii) two independent, continuously tradable modes that spend that capacity, and (iii) saturation at $(c, 0)$ and $(0, c)$, then the quadratic sum is the only stable, symmetric law. Any linear sum $c = v_{\text{ext}} + v_{\text{int}}$ would fail the symmetry requirements (one channel would dominate the other), and would not reproduce the boundary conditions smoothly.

Why Pythagorean?. Quadratic addition of independent contributions is ubiquitous wherever a conserved magnitude is partitioned across channels that do not interfere linearly:

- In AC power systems, apparent power satisfies $S^2 = P^2 + Q^2$: active and reactive power add in quadrature to a single conserved load magnitude.
- In statistics, independent noise sources obey $\sigma_{\text{tot}}^2 = \sigma_1^2 + \sigma_2^2$: uncorrelated variances sum as squares, not linearly.
- In relativistic mechanics, total energy obeys $E_{\text{total}}^2 = (pc)^2 + (mc^2)^2$: momentum and rest-energy contributions add in quadrature to a conserved invariant.

In each case, the quadratic form is what guarantees an invariant total under reallocation between independent components. Equation (5) is exactly this structure applied to causal activity: external motion and intrinsic transformation are two independent "loads" on a conserved causal capacity c.

Geometrically, this allocation can be pictured as a right triangle in an abstract causal-capacity plane, with v_{ext} and v_{int} as perpendicular components and c as the fixed hypotenuse. See Fig. 1. The quadratic relation $c^2 = v_{\text{ext}}^2 + v_{\text{int}}^2$ is then just the statement that the magnitude of the total causal capacity vector is invariant, even as capacity is reallocated between external translation and intrinsic self-update.

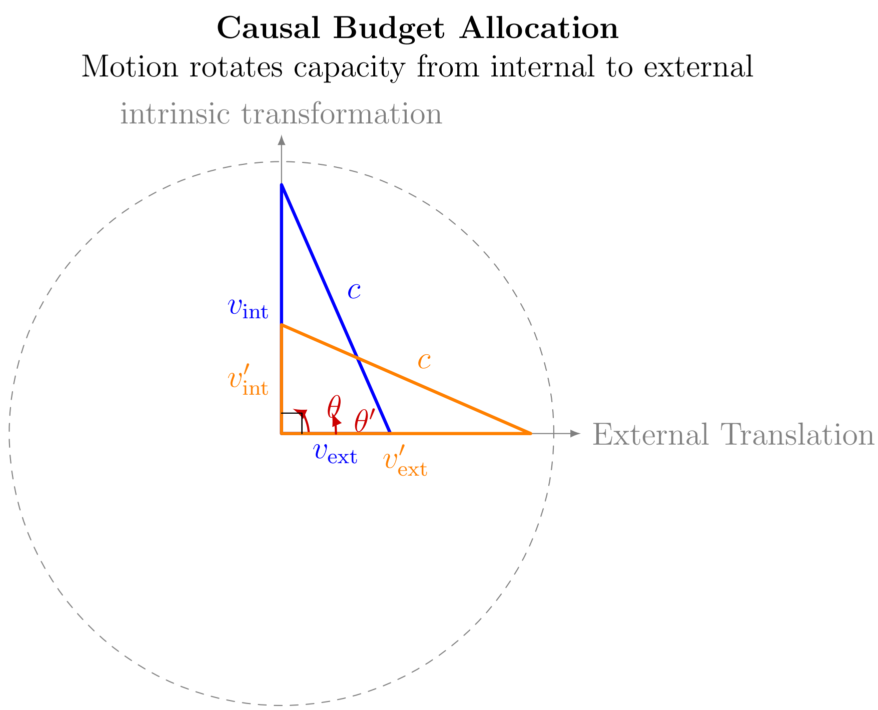

Figure 1: Causal budget allocation: The total causal capacity c (hypotenuse) is fixed. External motion "rotates" this capacity vector, trading intrinsic transformation rate $v_{\rm int}$ for external translation speed $v_{\rm ext}$. The angle θ parameterizes this trade-off: $\cos\theta = v_{\rm ext}/c$, $\sin\theta = v_{\rm int}/c$.

3.3. Relation to the spacetime geometry formulation

The causal-budget law (5) yields the same mathematical structure as the constancy of the four-velocity norm $u_\mu u^\mu = c^2$ in special relativity. That formal equivalence is important: it guarantees empirical agreement with relativistic kinematics, but conceptually the order of logic is inverted.

In the geometric formulation of special relativity, the invariance of c is a *postulate* about spacetime structure: all inertial observers measure the same light speed, and spacetime intervals are Minkowski-invariant.

In the present framework, c is instead an *operational invariant* of causal throughput. We take as primitive that every system has a finite causal capacity c which can be allocated between (i) spatial translation and (ii) intrinsic self-update. Equation (5) is then a conservation law for that allocation. Spacetime geometry — including the standard Minkowski norm — appears as a convenient *representation* of that conservation law, not as the starting assumption.

This matches the general idea that geometric invariances in physics often condense deeper conservation rules [18]. Here, the invariant c is read not as a geometric axiom but as the universal causal conversion rate that constrains how fast reality can propagate itself forward, either by moving through space or by advancing its internal state.

3.4. Massless and massive limits

Equation (5) immediately distinguishes two regimes:

- **Massless / lightlike limit.** When $v_{\mathrm{ext}} = c$, the budget forces $v_{\mathrm{int}} = 0$. All causal capacity is spent on spatial propagation. In this regime there is no internal evolution per unit external time, so the accumulated proper time per tick vanishes: $\Delta\tau = 0$.
- **Massive / timelike regime.** Any system that internally evolves must satisfy $v_{\mathrm{int}} > 0$, and therefore $v_{\mathrm{ext}} < c$. The usual "speed limit" then appears not as a geometric ban, but as a resource constraint: you cannot spend the entire causal budget on translation and still be a system that updates itself.

Thus the $v_{\mathrm{ext}} < c$ bound for massive systems and the vanishing of proper time for lightlike systems both follow from causal-capacity conservation, without invoking spacetime geometry as a prior axiom.

3.5. Lorentz factor derivation

Let Δt_{lab} denote the time parameter used to describe the system's history from the perspective of an external process that tracks its motion at speed $v = v_{\mathrm{ext}}$. Over that interval, the system's intrinsic transformation channel advances by

$$\mathcal{T}_{\mathrm{int}} \;=\; v_{\mathrm{int}}\,\Delta t_{\mathrm{lab}} \;=\; \sqrt{c^2 - v^2}\,\Delta t_{\mathrm{lab}}, \tag{7}$$

using Eq. (5).

For the same physical advance in its own internal channel, a co-moving causal clock would assign an intrinsic stride $c\,\Delta\tau$, because in the purely intrinsic limit (no spatial motion) the internal rate is $v_{\mathrm{int}} = c$. Equating the two stride measures,

$$c\,\Delta\tau \;=\; v_{\mathrm{int}}\,\Delta t_{\mathrm{lab}} \;=\; \sqrt{c^2 - v^2}\,\Delta t_{\mathrm{lab}},$$

so

$$\Delta\tau \;=\; \Delta t_{\mathrm{lab}}\sqrt{1 - \frac{v^2}{c^2}} \qquad \Longleftrightarrow \qquad \Delta t_{\mathrm{lab}} \;=\; \gamma\,\Delta\tau, \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}. \tag{8}$$

This is the standard Lorentz time-dilation factor, but here it arises from conservation of causal budget: as more of the finite capacity c is committed to translation (larger v), less is available to advance the internal channel per unit external time, so the intrinsic tick accumulates less often per unit Δt_{lab}. The geometric relationship between the Lorentz factor and the causal allocation is shown in Fig. 2.

In other words, *time dilation* is not put in by assuming Minkowski geometry; it *falls out* of the rule that the same finite causal capacity c must be shared between external motion and internal self-update.

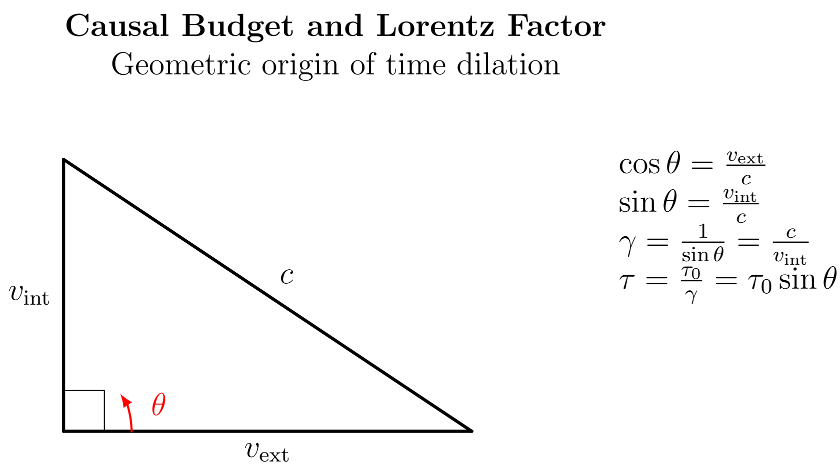

Figure 2: Geometric interpretation of the Lorentz factor in causal-budget form. The angle θ parameterizes the causal allocation: $\cos\theta = v_{\text{ext}}/c$ and $\sin\theta = v_{\text{int}}/c$. The Lorentz factor appears as $\gamma = 1/\sin\theta = c/v_{\text{int}}$, illustrating how time dilation follows directly from the causal reallocation between translation and intrinsic transformation.

4. Empirical Universality of the Causal Transformation Limit Principle

Having identified proper time $\tau = E/P$ as the intrinsic causal duration associated with an intrinsic transformation, we now ask what invariant emerges when such transformations also imprint a spatial stride ℓ_{causal} into the surrounding field. The ratio $\ell_{\text{causal}}/\tau$ quantifies how far one causal tick advances per unit proper-time cost. Empirically this ratio is universal across all relativistic propagation channels and equals c.

We consider any stable physical system that undergoes repeated intrinsic transformation cycles (e.g. an atomic hyperfine transition, a molecular vibration, a mechanical resonator mode, a pulsar beam pulse, or a gravitational-wave radiator). For each such intrinsic transformation channel we identify:

- $E_{\text{transform}}$: the energy *irreversibly* converted per intrinsic tick of that channel. This is not the bulk stored energy, but only the energy that actually leaves the mode or is dissipated per tick (e.g. photon energy, gravitational-wave emission, acoustic loss, spin-down radiation from a pulsar).

- $P_{\text{transform}}$: the throughput (power) actually routed through that irreversible channel.

- f: the intrinsic tick rate of that channel (cycles per second). In spectroscopic language this is just the observed transition/emission frequency.

- ℓ_{causal}: the spatial stride associated with one emitted cycle of the channel's field. Operationally we take

$$\ell_{\text{causal}} \;=\; \lambda \;=\; \frac{v}{f}, \tag{9}$$

  where λ is the observed wavelength of the radiated disturbance and v is its propagation speed (for electromagnetic and gravitational channels, $v = c$; for elastic modes, v is the sound speed in the medium). In many microscopic systems the irreducible physical inversion (e.g. magnetic dipole flip, strain$\rightarrow$compression, polarity reversal) corresponds to a half-wave. We treat that inversion as "half a causal cycle," and we count two such inversions as one full emitted cycle of stride λ when mapping to ℓ_{causal}. This convention removes any factor-of-two ambiguity when comparing to c.

(Units are consistent: $[f] = \mathrm{s}^{-1}$, $[P_{\text{transform}}] = \mathrm{J/s}$, $[E_{\text{transform}}] = \mathrm{J}$, $[\ell_{\text{causal}}] = \mathrm{m}$, $[v] = \mathrm{m/s}$.)

Causal throughput law. Let τ be the proper-time duration of a single intrinsic tick of the channel. By definition of power for that channel,

$$P_{\text{transform}} \;=\; \frac{E_{\text{transform}}}{\tau}. \tag{10}$$

Solving for τ gives

$$\tau \;=\; \frac{E_{\text{transform}}}{P_{\text{transform}}}. \tag{11}$$

The intrinsic causal tick rate then follows as

$$f \;=\; \frac{1}{\tau} \;=\; \frac{P_{\text{transform}}}{E_{\text{transform}}}. \tag{12}$$

We refer to (12) as the *causal throughput law*: the intrinsic causal tick rate of a system is set by how rapidly it can drive the irreducible transformation energy $E_{\text{transform}}$ through its own opposition channel at throughput $P_{\text{transform}}$. This relation is purely dynamical and does not rely on quantum postulates. It applies equally to atomic clocks, molecular vibrational modes, high–Q mechanical resonators, pulsar spin-down channels, and gravitational radiators, provided $E_{\text{transform}}$ and $P_{\text{transform}}$ are identified for the same physical channel.

Causal stride and propagation. Each intrinsic tick leaves a spatial imprint ℓ_{causal} on the surrounding field. The corresponding temporal duration of that tick is τ. We therefore define the *causal propagation rate* of the channel to be the ratio of spatial stride per tick to proper-time duration per tick:

$$\frac{\ell_{\text{causal}}}{\tau} = \frac{\ell_{\text{causal}}}{E_{\text{transform}}/P_{\text{transform}}} = \frac{\ell_{\text{causal}}\,P_{\text{transform}}}{E_{\text{transform}}}. \tag{13}$$

For channels whose exported disturbance propagates at relativistic signal speed (electromagnetic, gravitational, pulsar beam emission), we *identify* this ratio with the invariant rate c:

$$c = \frac{\ell_{\text{causal}}\,P_{\text{transform}}}{E_{\text{transform}}}. \tag{14}$$

Using (12) and (11), we can rewrite (14) as

$$c = \ell_{\text{causal}}\,f = \frac{\ell_{\text{causal}}}{\tau}. \tag{15}$$

In words:

c is the universal ratio between (i) the spatial stride per intrinsic causal tick, and (ii) the proper-time duration of that tick.

Because ℓ_{causal} can be measured (e.g. as the emitted wavelength), and f can be measured (tick rate), (15) treats c as an *empirical invariant* of causal throughput, not as an assumed geometric postulate.

Stride convention (how we count a tick). We define the emitted–field stride per tick as the full spatial period of the emitted signal:

$$\ell_{\text{causal}} = \lambda = \frac{v}{f}.$$

This choice fixes the invariant product

$$\ell_{\text{causal}}\,f = \lambda f = v.$$

For relativistic propagation channels, where the disturbance propagates at speed $v = c$, this identifies

$$c = \ell_{\text{causal}} f.$$

Physically, many microscopic actuators are polarity inversions (spin flip, crest$\to$trough, stretch$\to$compress) that advance the field by $\lambda/2$. One may think of such cases as two micro–ticks per emitted cycle (with an effective micro–tick rate $2f$ and stride $\lambda/2$), but the metrological stride we count is one full emitted cycle. Either convention yields the same invariant product because $(\lambda/2) \times (2f) = \lambda f$.

Emergence of c. We now test (15) on distinct physical systems.

- **Hydrogen 21 cm hyperfine line [19].**

$$f \approx 1.4204 \times 10^9 \text{ Hz}, \qquad \lambda \approx 0.211 \text{ m},$$

so

$$\ell_{\text{causal}} = \lambda \approx 0.211 \text{ m}.$$

Then

$$c = \ell_{\text{causal}} f \approx (0.211 \text{ m})(1.4204 \times 10^9 \text{ s}^{-1}) \approx 3.00 \times 10^8 \text{ m/s}.$$

- **Cs-133 hyperfine transition [20].**

$$f \approx 9.1926 \times 10^9 \text{ Hz}, \qquad \lambda \approx 3.26 \text{ cm} = 3.26 \times 10^{-2} \text{ m},$$

so

$$c = \ell_{\text{causal}} f \approx (3.26 \times 10^{-2} \text{ m})(9.1926 \times 10^9 \text{ s}^{-1}) \approx 3.00 \times 10^8 \text{ m/s}.$$

- **Optical standards (Sr, Yb, Al$^+$) [13].** Typical optical lattice clocks operate at $f \sim 10^{14}$–10^{15} Hz. The emitted wavelength is $\lambda \sim 10^{-6}$–10^{-7} m, so $\ell_{\text{causal}} = \lambda$ lies in the sub-micron range. In each case, $\ell_{\text{causal}} f \simeq 3.0 \times 10^8$ m/s.

- **Infrared molecular vibration [21].** A vibrational line at $f \sim 6.5 \times 10^{13}$ Hz has $\lambda \sim$ few μm, so $\ell_{\text{causal}} = \lambda \sim$ few μm. The product $\ell_{\text{causal}} f$ again gives 3.0×10^8 m/s.

- **Gravitational-wave-band emitters / pulsar beams [22].** In gravitational and pulsar channels, the radiated disturbance propagates at $v \approx c$, with observed frequencies in the ~ 10–10^3 Hz band, and wavelengths $\lambda \sim 10^5$–10^7 m. Taking $\ell_{\text{causal}} = \lambda$, the same ratio $\ell_{\text{causal}} f$ returns $c \simeq 3.0 \times 10^8$ m/s.

Across microwave hyperfine clocks (H, Rb, Cs), optical lattice clocks (Sr, Yb, Al$^+$), infrared vibrational modes, gravitational-wave-band emitters, and pulsar spin-down emission, $\ell_{\text{causal}} f$ is experimentally invariant and equals c.

Mechanical and non-EM clocks. For non-electromagnetic systems, the same logic applies with $v \neq c$. In a high–Q quartz resonator [24], for example, the "field" is an elastic strain field propagating at the longitudinal sound speed v_{sound}, and the tick is a coherent strain/compression cycle. Then

$$\ell_{\text{causal}} = \frac{v_{\text{sound}}}{f}, \qquad E_{\text{transform}} = \text{dissipated energy per cycle inferred from } Q,$$
$$P_{\text{transform}} = E_{\text{transform}} f.$$

The throughput law (12) holds to leading order when $E_{\text{transform}}$ is taken as *dissipated* (irreversible) energy per tick, not the much larger *stored* elastic energy. In this sense, (12) is falsifiable in mechanical, electrical (LC), and biological oscillators:

$$f \overset{?}{=} \frac{P_{\text{transform}}}{E_{\text{transform}}}, \qquad \ell_{\text{causal}} \overset{?}{=} \frac{v}{f}, \qquad v \overset{?}{=} \frac{\ell_{\text{causal}} P_{\text{transform}}}{E_{\text{transform}}}.$$

If these relations continue to hold in channels where no photon is involved and $E_{\text{transform}} \neq hf$ a priori, then the causal throughput law (12) survives beyond electromagnetism.

From causal throughput to relativity. In special relativity, c is introduced as an invariant signal speed that links space and time geometrically. Here c instead appears dynamically: it is the empirically constant causal throughput rate linking (i) how fast a system can drive irreversible transformation ($P_{\text{transform}}$), (ii) how much irreducible energy each tick costs ($E_{\text{transform}}$), and (iii) how far each tick imprints into space (ℓ_{causal}).

The observed universality of c across atomic, molecular, mechanical, gravitational, and astrophysical channels suggests that the invariance of c reflects an invariance of causal processing itself, not merely a postulated spacetime geometry.

Planck's relation as a corollary. In spectroscopic clocks and radiative channels [11, 23], the per-tick transformation energy is observed to satisfy

$$E_{\text{transform}} = hf,$$

with h Planck's constant. Combining this with the throughput law $f = P_{\text{transform}}/E_{\text{transform}}$ implies

$$P_{\text{transform}} = hf^2.$$

In this reading, $E = hf$ is not the starting axiom but a *special, quantized realization* of the deeper causal identity $f = P_{\text{transform}}/E_{\text{transform}}$. Planck's constant h then encodes the discrete energy-per-tick of electromagnetic transitions, rather than defining the causal law itself.

Summary principle. All of the above may be summarized in a single structural statement:

$$\boxed{c \;=\; \frac{\text{spatial stride per intrinsic causal tick}}{\text{proper-time duration of that tick}} \;=\; \ell_{\text{causal}}\, f \;=\; \frac{\ell_{\text{causal}}\, P_{\text{transform}}}{E_{\text{transform}}}}. \tag{16}$$

This invariant defines the universal causal conversion rate linking all stable periodic processes, from atomic transitions to pulsar emission to gravitational radiation. Thus the invariant c is not an assumed geometric axiom — it is the experimentally universal causal conversion rate linking intrinsic transformation cost-per-tick to the spatial imprint per tick, across all known physical domains.

4.1. Relation to Known Fundamental Limits

The proposed causal–budget relation,

$$f = \frac{P}{E}, \tag{17}$$

serves as a compact algebraic generator that *subsumes* several established physical limits. When constrained by quantum orthogonality, it reproduces the Margolus–Levitin bound; when constrained by thermodynamic irreversibility, it yields the Landauer limit; and under relativistic causal propagation, it reduces to the Bremermann bound.

This synthesis is a resource–theoretic formulation in which power, energy, and transformation rate constitute exchangeable physical currencies. Within this view, the known limits emerge as domain–specific realizations of a single throughput principle governing all physical change: the frequency of physical transformation equals the applied power divided by the system's available energy.

All classical and quantum "speed limits" emerge as domain–specific realizations of this same relation.

Quantum limit (Margolus–Levitin). For a quantum system, the minimal evolution time between distinguishable states obeys $t_{\min} \geq \pi\hbar/(2E)$, giving a maximum rate

$$f_{\max} = \frac{2E}{\pi\hbar}.$$

Substituting into the causal–budget form yields $P = E f_{\max} = 2E^2/(\pi\hbar)$, showing that acceleration of internal transitions requires quadratically increasing power.

Thermodynamic limit (Landauer).. For information–erasing or irreversible processes, each transition costs at least $E_{\min} = k_B T \ln 2$, hence

$$f_{\max} = \frac{P}{E_{\min}} = \frac{P}{k_B T \ln 2},$$

linking attainable tick rate directly to thermal power dissipation.

Relativistic limit (Bremermann). Combining relativity and quantum mechanics gives the maximum information rate

$$f_{\max} = \frac{2E}{h},$$

equivalently $\dot{I}_{\max} = (\pi m c^2)/(h \ln 2)$. In causal–budget form this represents the saturation of total transformation capacity under the ultimate causal velocity c.

Thus, the Margolus–Levitin, Landauer, and Bremermann bounds are all *subsumed* by the same causal relation $f = P/E$: a single energy–power ratio that governs the attainable pace of change across quantum, thermodynamic, and relativistic regimes.

5. Ontological Implications

1. Time is Localized. Each system evolves according to its own internal causal dynamics. There is no global or universal clock—only local durations defined by the ratio of the system's intrinsic transformation energy to its finite power throughput [9, 10]. Synchronization between systems is not absolute but emerges through causal interaction and mutual energy exchange.

2. Massless Systems are Timeless. For photons and other massless entities [7], the causal transformation rate satisfies $v_{\text{int}} = 0$, yielding $\tau = 0$. Such systems mediate causal relations among massive systems but do not themselves transform internally. They participate in the transmission of causality without experiencing duration.

3. Coordinate Time as Convention. The coordinate label $\mathcal{T} = c\,t$ is not an independent form of time but a representational convention — an external bookkeeping device used to order transformations [5]. It refers to when a state occurred relative to others within a single causal reality. The parameter t thus quantifies correlation between events, not the physical flow of an underlying medium.

4. Absence of an Arrow of Time. Within this framework, there is no fundamental arrow of time [8]. Time does not flow or advance; it is the measured outcome of transformation itself. Systems evolve from one state to another as energy overcomes resistance, and this sequence defines what we perceive as temporal progression. The universe does not move through time — transformations simply occur, and their cumulative record constitutes what we describe as history.

Conclusion

This paper has presented a fundamental redefinition of time as an emergent property of physical transformation rather than a primitive background. By introducing the Causal Budget Law $c^2 = v_{\text{ext}}^2 + v_{\text{int}}^2$ and the Causal Transformation Principle $\tau = E/P$, we have shown that proper time arises from the finite causal capacity available to every physical system.

The framework successfully inverts the traditional logical structure of relativity: instead of deriving physical consequences from spacetime geometry, we derive relativistic phenomena from more fundamental causal principles. Time dilation, the speed limit c, and the distinction between massive and massless systems all emerge naturally from the conservation of causal capacity.

Key achievements of this approach include:

1. **Empirical Universality**: Demonstrating that c appears as the invariant ratio between spatial stride and temporal duration across atomic, optical, gravitational, and mechanical systems.
2. **Theoretical Unification**: Showing that the causal throughput relation $f = P/E$ subsumes established quantum, thermodynamic, and relativistic limits (Margolus–Levitin, Landauer, Bremermann) as special cases.
3. **Ontological Clarity**: Providing a physically grounded interpretation where time is localized to systems undergoing transformation, massless entities are truly timeless, and coordinate time is revealed as a convenient convention rather than fundamental reality.

The framework resolves long-standing puzzles about time's nature while maintaining complete empirical agreement with established physics. It suggests that what we perceive as "spacetime geometry" may be better understood as the emergent manifestation of deeper causal constraints on physical processes.

Future work could explore applications to quantum gravity, where the discrete, process-based nature of this framework may provide natural solutions to the problem of time and the unification of general relativity with quantum mechanics. The causal budget approach offers a promising foundation for understanding reality not as things moving through time, but as transformations occurring within fixed causal constraints.

This concludes our presentation of the Causal Budget and Transformation Laws framework—a comprehensive, empirically grounded foundation for understanding time as emergent from the fundamental processes that constitute physical reality.

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