

Flow, Orientation, Irreversibility, and the Thermodynamic Arrow of Time

Four Failed Attempts at Deriving Orientation, One Operational Control
Case, and the Orientation Problem

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Note on provenance. This note grew out of a critical revision of the manuscript *A Processual Self-Referential Ontology* and a multi-stage discussion with the AI thinking partners ChatGPT (Aion), Claude, and DeepSeek. The calculations, conclusions, and literature references presented here were checked separately against the initial proposals. Responsibility for the final presentation rests with the author.

Abstract

The starting point is an attempt to derive temporal order from irreversibility, or from a loss of possibilities. The analysis shows that four distinct notions must be kept separate: *temporal flow*, *orientation*, *irreversibility*, and the *thermodynamic arrow of time*. Four natural information-theoretic attempts at deriving an orientation are examined: a prospective possibility counter $-\ln P(A)$, nested history spaces, relative entropy on increasing algebras, and a data-processing/Petz deficit. None of these four candidates generates a direction of time. As a fifth case, relative entropy between forward and reversed processes is considered. This is not a failed formalism but a successful operational measure of irreversibility, and for that very reason it exposes the boundary of the orientation problem: forward and backward must already be defined. A simple covariance lemma isolates the minimal symmetry obstruction. Known microscopic T violation is discussed as a control case: it can provide a fundamental process asymmetry, but it is neither irreversibility nor an established explanation of the macroscopic entropy arrow. This note does not claim a new theory of time. It documents which natural identifications fail and what additional structure is required for an orientation to be selected.

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1. The Starting Problem

The original manuscript, *A Processual Self-Referential Ontology* (PSO), pursues the idea that processes rather than static states should be ontologically privileged, and that time should not be assumed as a primitive background quantity but reconstructed as an ordering of irreversible events [1]. In the most recent version, an event is described as a non-invertible restriction of a relational possibility space; time is then supposed to arise as a partial order of such events. At the same time, however, the formal section introduces quantities such as $M(t)$, $A_{t+1} \subseteq A_t$, $\dot{M}(t)$, and time-dependent transition matrices $P(t)$. It therefore presupposes precisely the temporal parametrization that is later meant to be derived.

Discussion of this problem initially led to several repair attempts. The decisive point, however, was not the increasing mathematical abstraction, but the repeated observation that a measure defined on an already directed structure does not itself generate the direction. This yields the central conceptual distinction of the present note:

$$\boxed{\text{flow} \neq \text{orientation} \neq \text{irreversibility} \neq \text{thermodynamic arrow of time}} \quad (1)$$

The following sections sharpen these four levels and then test them against four repair candidates and one operational control case. The selection explicitly does *not* claim to survey all information-theoretic or philosophical approaches to the arrow of time. It consists of the four natural constructions that arose while attempting to repair the formal PSO idea, supplemented by an established control case.

2. Four Distinct Problems

2.1. Temporal flow

A *temporal flow* is, at first, merely a parametrized evolution. Formally, for example, it may be a one-parameter group

$$\alpha_t, \quad t \in \mathbb{R}, \quad \alpha_{t+s} = \alpha_t \circ \alpha_s. \quad (2)$$

In algebraic quantum statistical mechanics, Tomita–Takesaki theory associates a canonical modular automorphism group σ_t^ω with a suitable von Neumann algebra $\mathcal{M}$ and a faithful normal state ω . Connes and Rovelli proposed interpreting such a state-dependent flow as physical *thermal time* [8].

A flow by itself, however, does not yet single out a thermodynamic arrow. For a group,

$$\alpha_t^{-1} = \alpha_{-t}, \quad (3)$$

so both parameter directions are mathematically available.

2.2. Orientation

By *orientation* we mean a physical distinction between the two directions. An oriented dynamics may, for example, possess transition probabilities that are not invariant under an appropriate T transformation. Experimentally established T violation in the neutral B -meson system provides one example [14].

Orientation is weaker than irreversibility. A unitary theory may violate T while still possessing invertible time evolution. Different transition rates for a process and its T -conjugate do not imply that state information is fundamentally lost.

2.3. Irreversibility

Irreversibility requires more than the existence of a sign. What matters is that, within a physically admissible description, a transition cannot be fully reconstructed or inverted. Depending on context, this may be described through coarse-graining, open dynamics, measurement, dissipation, information loss under a channel, or the statistical distinguishability of forward and reversed processes.

In modern information theory, the question of *recoverability* is precise: a data-processing inequality can be strict when the applied map loses relevant distinguishability. That fact alone, however, does not turn the channel into a fundamental arrow of time.

2.4. The thermodynamic arrow of time

The thermodynamic arrow is the macroscopic regularity that, under appropriate conditions, systems typically evolve toward higher entropy. Explaining this regularity is a distinct problem in statistical mechanics and cosmology. Price, Albert, and Wallace belong to a broad literature that assesses in different ways the roles of special boundary or initial conditions, statistical mechanics, and cosmological conditions [18, 17, 19].

The four levels in Eq. (1) therefore cannot be identified without further argument.

3. Candidate I: A Prospective Possibility Counter

The most recent PSO version effectively defines a possibility counter as

$$M = -\ln P(A), \tag{4}$$

with a nested sequence of accessible state sets

$$A_{n+1} \subseteq A_n. \tag{5}$$

The smaller the remaining probability volume $P(A)$, the larger M becomes.

For a uniform measure on a finite state space Ω ,

$$P(A) = \frac{|A|}{|\Omega|}, \tag{6}$$

and hence

$$M = \ln |\Omega| - \ln |A|. \tag{7}$$

If $|A|$ is identified with a macroscopically compatible phase-space volume, the Boltzmann entropy is, up to a constant,

$$S_B = k_B \ln |A|. \tag{8}$$

Therefore

$$M = \ln |\Omega| - \frac{S_B}{k_B}. \quad (9)$$

Thus M increases precisely when this phase-space volume, and therefore S_B , decreases. This construction cannot therefore be interpreted at the same time as ordinary thermodynamic entropy production.

A further conceptual shift is involved. A prospective A denotes future accessibility, whereas the original PSO interpretation referred to a loss of reconstructible past alternatives. These are different quantities.

Diagnosis. Equation (4) can define a surprisal or constraint measure. Without additional structure, it neither generates a temporal ordering nor is it automatically thermodynamic entropy.

4. Candidate II: Nested History Spaces

A natural repair is to consider not future states, but past histories compatible with present records. The language of alternative, coarse-grained histories is closely related to the decoherent-histories program of Gell-Mann and Hartle [4, 5]. The explicit relation between decoherence and physically stored records was studied, among others, by Halliwell [6]; Zurek’s quantum-Darwinism program describes the redundant proliferation of such environmental records [7]. The nesting construction below is not attributed to those works; it is tested here as a separate repair attempt for the PSO idea. Let

$$\mathcal{H}_e = \{\text{histories compatible with the records at } e\}. \quad (10)$$

If for two events one assumes

$$e \prec f \implies \mathcal{H}_f \subseteq \mathcal{H}_e, \quad (11)$$

then one may define, for example,

$$\Delta M_{e \rightarrow f} = -\ln P(\mathcal{H}_f) + \ln P(\mathcal{H}_e) \geq 0. \quad (12)$$

The monotonicity is mathematically correct. But the direction is already fully encoded in assumption (11). In order to interpret $\mathcal{H}_f \subseteq \mathcal{H}_e$ as a directed sequence of record states, one must already know which event counts as later, or in which direction records accumulate.

Moreover, real records can be erased, overwritten, or thermally destroyed. A global nesting condition therefore does not hold in general.

Diagnosis. Nested histories can parametrize an already given informational arrow. They do not derive it.

5. Candidate III: Relative Entropy on an Algebra Filtration

The algebraic version replaces classical state sets by von Neumann algebras. Araki defined relative entropy for general von Neumann algebras and proved, among other properties, its monotonicity [2]; Uhlmann established related monotonicity results for unital completely positive maps [3]. For an inclusion

$$\mathcal{A}_e \subseteq \mathcal{A}_f \quad (13)$$

and states ω, σ , one correspondingly has

$$D_{\mathcal{A}_e}(\omega \parallel \sigma) \leq D_{\mathcal{A}_f}(\omega \parallel \sigma). \quad (14)$$

Defining

$$M(e) = D_{\mathcal{A}_e}(\omega \parallel \sigma) \quad (15)$$

therefore gives

$$\Delta M_{e \rightarrow f} \geq 0. \quad (16)$$

This, however, is a theorem about information access under algebra inclusion, not about time. Neither dynamics nor irreversibility enters. An arbitrarily increasing family of subsystem algebras is sufficient.

5.1. Finite-qubit test

For

$$\mathcal{A}_k = M_2(\mathbb{C})^{\otimes k} \otimes I \quad (17)$$

and the maximally mixed reference state

$$\sigma_k = \frac{I}{2^k}, \quad (18)$$

one has

$$M_k = D\left(\rho_k \parallel \frac{I}{2^k}\right) \quad (19)$$

$$= \text{Tr}(\rho_k \ln \rho_k) - \text{Tr}\left(\rho_k \ln \frac{I}{2^k}\right) \quad (20)$$

$$= -S_{\text{vN}}(\rho_k) + k \ln 2. \quad (21)$$

In bits,

$$\boxed{M_k = k - S_{\text{vN}}(\rho_k)}. \quad (22)$$

Thus, in this model, the proposed quantity is exactly the familiar negentropy relative to the maximally mixed state.

For the product state $|000\rangle$,

$$(M_1, M_2, M_3) = (1, 2, 3), \quad (23)$$

even though no decoherence, record formation, or physical irreversibility occurs. The monotonicity arises solely because progressively more pure subsystems are included in the accessible algebra.

For

$$|\text{GHZ}\rangle = \frac{|000\rangle + |111\rangle}{\sqrt{2}}, \quad (24)$$

one obtains

$$(M_1, M_2, M_3) = (0, 1, 3). \quad (25)$$

The increase reflects newly accessible correlations and entanglement, not an arrow of time.

Diagnosis. Araki monotonicity is mathematically appropriate and, in type-III settings, substantially more general than finite-dimensional density-matrix formulas. As an argument

for an arrow of time, however, it is empty as long as the directed family of algebras is itself assumed.

6. Candidate IV: The Data-Processing/Petz Deficit

A sharper candidate is not relative entropy itself, but its loss under a channel. For the partial trace $AB \rightarrow A$ and reference states

$$\sigma_{AB} = I/4, \quad \sigma_A = I/2, \quad (26)$$

we define the data-processing deficit

$$\delta_{AB \rightarrow A} = D(\rho_{AB} \| \sigma_{AB}) - D(\rho_A \| \sigma_A). \quad (27)$$

Using Eq. (22), in bits,

$$\delta_{AB \rightarrow A} = [2 - S(AB)] - [1 - S(A)] \quad (28)$$

$$= 1 - S(B|A). \quad (29)$$

For three illustrative pure states one obtains:

State	$\delta_{12 \rightarrow 1}$	$\delta_{123 \rightarrow 12}$
$ 000\rangle$	1 bit	1 bit
$ \text{GHZ}\rangle$	1 bit	2 bit
$ W\rangle = (001\rangle + 010\rangle + 100\rangle)/\sqrt{3}$	1 bit	1.9183 bit

For the W state,

$$S(\rho_1) = S(\rho_{12}) = h_2(1/3) \approx 0.9183 \text{ bit}. \quad (30)$$

The decisive counterexample is again $|000\rangle$. The deficit is positive even though the underlying situation can be entirely static and reversible. The reason lies in the reference state: the recovery structure associated with the maximally mixed reference does not reconstruct the discarded qubit as the actually pure state. What is measured is therefore non-sufficiency, or loss of distinguishability relative to a reference pair, not the occurrence of a physically irreversible event.

Petz's work characterizes equality conditions for the data-processing inequality and the possibility of exact recovery [12]. This theory precisely answers when information is preserved under a given channel. It does not answer why the channel should carry a fundamental temporal orientation.

Diagnosis. Recoverability is an appropriate tool for quantifying information loss. It does not generate an orientation of the process.

7. Control Case V: Forward/Reverse Distinguishability

The fifth case is the first one that genuinely captures irreversibility operationally. Benoist, Jakšić, Pautrat, and Pillet study repeated quantum measurements and compare the statistics

of a process with those of an appropriate outcome-reversed process [13]. Relative entropy and related Rényi quantities quantify how well the forward and reversed processes can be distinguished by hypothesis testing; the authors relate this to entropy production, large-deviation principles, and Chernoff and Hoeffding exponents.

Schematically, the relevant structure is

$$\Sigma \sim D(P_{\rightarrow} \| P_{\leftarrow}). \quad (31)$$

If the process is statistically indistinguishable from the constructed reversed process, this asymmetry vanishes; the more distinguishable they are, the stronger the operational arrow of time.

This is also precisely where the limit of the original PSO program becomes visible: in order to compare $P_{\rightarrow}$ with $P_{\leftarrow}$, the two orientations must already have been defined. The formalism measures the arrow; it does not generate the meanings of “forward” and “backward” from unoriented data.

Diagnosis. The strongest of the five cases examined is also the one that most clearly shows that *measuring an arrow* and *generating an orientation* are different tasks.

8. The Orientation Lemma

The preceding examples suggest an abstract minimal form of the problem.

Lemma (orientation from symmetric data). Let X be a class of fundamental data and

$$R : X \rightarrow X, \quad R^2 = \text{id}, \quad (32)$$

an involution that exchanges a possible orientation. Suppose one seeks a covariant orientation assignment

$$F : X \rightarrow \{+, -\} \quad (33)$$

with

$$F(Rx) = -F(x). \quad (34)$$

For a fixed point x satisfying

$$Rx = x, \quad (35)$$

no such unique assignment exists.

Proof. Covariance implies

$$F(x) = F(Rx) = -F(x), \quad (36)$$

which is impossible for $F(x) \in \{+, -\}$. $\square$

The lemma is elementary. Its physical content depends entirely on whether the underlying data actually contain a fixed point of orientation reversal. It therefore does not say that fundamental orientation is impossible. It says only:

Fully orientation-symmetric data alone do not determine a unique orientation.

(37)

A direction then requires additional asymmetric structure: a state, boundary conditions,

reservoir conditions, external driving, explicitly T -violating dynamics, or some other symmetry breaking. Logically, this has the same form as a selection problem under symmetry breaking: symmetric fundamental equations or data may admit asymmetric states, yet starting from a symmetric fixed point they do not covariantly select a unique branch. This does *not* claim that the thermodynamic arrow of time is, in the technical quantum-field-theoretic sense, an instance of spontaneous symmetry breaking; the analogy concerns only the structure of the selection problem.

Scope of the lemma in the modular case. The lemma becomes applicable only after a concrete orientation-reversing involution R has been specified for the chosen data class. For an algebra $\mathcal{M}$ without a state, there is as yet no state-dependent modular flow whose orientation could be discussed. For the pair $(\mathcal{M}, \omega)$, Tomita–Takesaki theory does provide a canonical flow σ_t^ω , but the present note identifies no intrinsic physical involution R that, within precisely this data class, reverses the flow $t \mapsto -t$ while also producing a fixed point in the sense of the lemma. In particular, modular conjugation J is not such a time-reversal operator: from $J\Delta J = \Delta^{-1}$ and the antiunitarity of J , one obtains for imaginary powers $J\Delta^{it}J = \Delta^{it}$. The fixed-point case of the lemma is therefore *not* assumed here to be established for $(\mathcal{M}, \omega)$. Rather, the modular control case separates two tasks: Tomita–Takesaki theory supplies a flow; physically selecting a sign of that flow is an additional question.

9. Modular Flow Is Not a Thermodynamic Arrow

Tomita–Takesaki theory is particularly instructive here because it shows that even a flow canonically constructed from an algebra and a state does not automatically yield irreversibility. For suitable $(\mathcal{M}, \omega)$, one obtains a modular group

$$\sigma_t^\omega, \quad t \in \mathbb{R}. \quad (38)$$

Connes and Rovelli use precisely this structure to formulate the thermal-time hypothesis [8].

The flow, however, is a group of automorphisms and is therefore invertible. It primarily addresses the problem of flow, not that of an irreversible thermodynamic arrow.

Half-sided modular inclusions provide another important control case. We use the convention $\sigma_t(x) = \Delta^{it}x\Delta^{-it}$; sign conventions for half-sidedness differ in the literature. Wiesbrock considered inclusions $\mathcal{N} \subset \mathcal{M}$ satisfying a condition of the form

$$\Delta_{\mathcal{M}}^{it}\mathcal{N}\Delta_{\mathcal{M}}^{-it} \subseteq \mathcal{N} \quad (t \geq 0) \quad (39)$$

and, under suitable assumptions, derived a one-parameter translation group with positive generator [9, 10]. The original publication contained a gap in the proof; Araki and Zsidó later closed it and generalized the result to common faithful normal semifinite weights [11]. For the orientation problem defined here, the conclusion is unchanged: half-sidedness is already formulated relative to one sign of the modular parameter and therefore does not derive orientation from completely unoriented data.

The key distinction therefore remains:

$$\text{canonical flow} \not\Rightarrow \text{thermodynamic arrow}. \quad (40)$$

10. Control Case: Fundamental T Violation

The orientation lemma assumes that the relevant fundamental data are invariant under reversal of orientation. This assumption is not universally satisfied in actual particle physics. The Standard Model contains CP violation; under the usual CPT assumptions this entails T violation. In 2012, the BABAR Collaboration directly observed different probabilities for pairs of T -conjugate transitions in the neutral B -meson system [14]. Jarlskog had already introduced in 1985 a rephasing-invariant measure of CP violation in the quark sector [15].

Fundamental T violation makes a microscopic *orientation* possible in principle; such an orientation need not arise solely from cosmological boundary conditions. As order-of-magnitude reference values in the quark sector, the Particle Data Group gives the Jarlskog invariant as $J = (3.12^{+0.13}_{-0.12}) \times 10^{-5}$ for the CKM structure; for indirect CP violation in the neutral-kaon system, $|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$ [16]. These numbers are not universal measures of all observable T or CP asymmetries – individual dimensionless asymmetry parameters in neutral B systems can be substantially larger – but they identify the specific weak/CKM structure from which the known violation arises.

This point must not, however, be confused with irreversibility. Standard-Model time evolution is unitary. T violation means that a process and its T -conjugate do not have identical physics; it does not mean that time evolution ceases to be invertible or that information is fundamentally destroyed.

Nor is there an established mechanism by which the known weak T violation becomes the universal cause of the macroscopic entropy arrow. Thermal mixing of coffee and milk, diffusion, viscous dissipation, and ordinary heat flow are, in the physically relevant regimes, dominated by molecular and electromagnetic scattering and transport processes; the observed T violation in the weak/CKM sector provides no known amplification mechanism for these phenomena. The numerical scales quoted above are therefore control values only, not a no-go argument based on smallness.

The control case therefore shows that T violation can make a microscopic orientation possible in principle. It does not imply

$$T\text{-violation} \Rightarrow \text{irreversibility}, \quad (41)$$

and still less automatically

$$T\text{-violation} \Rightarrow \text{thermodynamic arrow}. \quad (42)$$

11. What Follows from Four Failed Attempts and One Control Case

The first four candidates do not fail by accident for four unrelated technical reasons. The fifth case, by contrast, is a successful operational measure of process asymmetry and serves as a control. Together, they illustrate different versions of the same conceptual conflation.

Candidate	What it actually measures / assumes	Why it does not generate orientation
$-\ln P(A)$	Constraint relative to a reference space	Direction and interpretation of A must already be fixed
History nesting	Loss of compatible histories	$\mathcal{H}_f \subseteq \mathcal{H}_e$ is already a directed record structure
Araki relative entropy on $\mathcal{A}_e \subseteq \mathcal{A}_f$	Distinguishability under increasing information access	Monotonicity follows from inclusion, without dynamics
Petz/DPI deficit	Loss of distinguishability / recoverability of a given channel	Positive even for static product states
Control: $D(P_{\rightarrow} \ P_{\leftarrow})$	Operational forward/reverse asymmetry	Works for irreversibility, but presupposes forward and reverse

Summary diagnosis. In all constructions examined here in which a monotone or information-theoretic measure is defined on an already directed filtration, channel, or forward/reverse pair, the orientation does not come from the measure itself. This statement is a diagnosis supported here by the four counterexamples and the control case, *not* a general theorem about every conceivable measure or dynamics.

The original PSO thesis

$$\text{irreversibility} \longrightarrow \text{temporal order} \quad (43)$$

is not supported by the constructions examined here.

11.1. Consequences for the Processual Self-Referential Ontology

The analysis does not imply that every process-ontological idea in the original manuscript must be discarded. It does, however, bear on one of its strongest central claims: that irreversibility, or vanishing possibilities, might simultaneously ground eventhood, temporal order, entropy, and later even spacetime geometry.

At least four levels must henceforth be kept distinct:

1. A theory may ontologically privilege processes and event relations without thereby explaining the thermodynamic arrow.
2. A partial order of events may represent a causal structure without explaining why one orientation is physically distinguished.
3. An information measure may be monotone on a directed structure without generating that structure.
4. An observed entropy arrow may follow from statistical and boundary conditions without defining a fundamental temporal metric.

The scientifically cautious conclusion at present is therefore not “PSO has been refuted”, but the narrower statement:

The formal realizations of the PSO idea examined so far provide no non-circular mechanism by which irreversibility alone generates a distinguished temporal orien-

tation. Several candidates reduce to familiar information-theoretic quantities or already presuppose the direction to be explained in their defining structure.

This is a negative result, but a testable one.

Scope and contribution. This note is intended as a critical technical companion to the PSO manuscript, not as a new theory of time. It claims historical priority neither for the fourfold distinction in Eq. (1) nor for the distinction between asymmetry in laws and asymmetry in boundary conditions. Its possible independent contribution is narrower: four orientation proposals that arose from attempts to repair the PSO idea are tested by short explicit calculations or structural counterarguments, while an established fifth formalism serves as a positive control. Particular emphasis is placed on separating *flow* from *orientation*. Whether this distinction, in precisely this form, has already been treated systematically in the philosophy-of-physics or AQFT literature remains a literature question and is not pre-empted here as a novelty claim.

12. Boundary Conditions and the Past-Hypothesis Family

For microscopically time-reversal-symmetric dynamics, the classical question is why macroscopic entropy gradients do not appear symmetrically in both directions. One major family of answers appeals to special initial or boundary conditions, often under the heading of the *Past Hypothesis*. Albert develops this strategy systematically in *Time and Chance* [17]; Price emphasizes the danger of temporal double standards and shifts the problem substantially toward cosmology [18]; Wallace discusses, in particular, the role of gravitational degrees of freedom and cosmological conditions [19].

This literature does not constitute a single closed standard answer. It contains substantial disagreement about the status, formulation, and explanatory power of such boundary conditions. For present purposes, a cautious statement is sufficient: if the relevant microscopic dynamics does not itself select an orientation, an explanation of the observed thermodynamic arrow requires additional time-asymmetric physical conditions.

Because known T violation exists, this must be formulated as a case distinction:

Case I: Orientation-symmetric fundamental data. By the lemma, a unique direction cannot follow from these data alone; additional asymmetry is required.

Case II: T -violating fundamental dynamics. A microscopic orientation may already reside in the laws. The transition from this orientation to macroscopic irreversibility and to the thermodynamic arrow nevertheless remains a separate problem.

This case distinction refers to whichever fundamental dynamics is actually being used. The experimentally established T violation of the Standard Model is explicitly *not* extrapolated here to the symmetry structure of an unknown more complete fundamental theory. Whether and in what form such a theory possesses an intrinsic T asymmetry remains open for the purposes of this note.

13. Open Research Question

After four failed attempts and the operational control case, a more precise question remains than in the original manuscript:

What minimal physical structure is required for a non-conventional, empirically distinguished process direction to arise from otherwise unoriented or reversible data, and under what additional conditions does such an orientation become a thermodynamic arrow?

(44)

This question itself separates into two parts:

A. Orientation

What data break the R symmetry so that $+/-$ become physically distinguishable?

B. Irreversibility

Once an orientation is given, what quantity measures the non-recoverable or statistically asymmetric part of the dynamics?

For B, powerful theories already exist: relative entropy, recovery, entropy production, fluctuation theorems, and hypothesis tests of the arrow of time. For A, the answer depends on the symmetry structure of the actual fundamental dynamics and on the physical boundary conditions.

14. Conclusion

The original attempt to ground time as a “geometry of vanishing possibilities” combined several distinct questions into a single image. The present analysis separates them. A flow is not yet an orientation. Orientation is not yet irreversibility. Irreversibility is not yet an explanation of the universal thermodynamic arrow.

The four failed attempts at deriving orientation and the positive control case together reveal a consistent pattern: the measures examined characterize constraint, distinguishability, recoverability, or forward/reverse asymmetry, but none of the tested constructions generates, from fully unoriented data alone, a physically distinguished sign. The successful operational measure – distinguishability between forward and reversed processes – makes this boundary especially clear.

The remaining research question is smaller than PSO but sharper: What minimal asymmetric physical structure makes orientation definable at all, and what additional conditions turn that orientation into macroscopic irreversibility? Only once this question is answered does it become meaningful to ask whether a processual ontology contributes further independent physical content.

A. Methodological Note on AI-Assisted Critical Evaluation

The development of this note yields a methodological lesson in addition to the substantive result. Several formally elegant proposals initially appeared to constitute progress until elementary

counterexamples or primary sources placed them in context. The productive steps included, in particular:

- the direct calculation $M_k = k - S_{\text{vN}}(\rho_k)$;
- the product-state countercheck for the Petz/DPI deficit;
- verifying that Araki monotonicity is a statement about information access, not about time;
- reading Benoist et al. directly on forward/reverse distinguishability;
- separating modular flow structure from the thermodynamic arrow;
- the control case of experimentally established T violation.

This suggests a working rule for further foundational work:

$$\boxed{\text{No new theoretical layer before a counterexample calculation or a primary source.}} \quad (45)$$

Linguistic coherence, mathematical elegance, or agreement among several models is no substitute for these two checks.

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