

# A Universal Phase Space for Representable Computation

Thermodynamic Coordinates for Comparing All Computational Systems

The RSC Framework: Theory, Methodology, and Universal Benchmarks

RSC Framework Development

*Generated through collaborative human-AI synthesis*

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## IMPORTANT NOTICE

This document was generated through extensive collaboration with Large Language Model AI systems (Claude, GPT, Grok). While care has been taken to ensure internal consistency, **all equations, theoretical claims, and numerical estimates should be independently verified** before use in research or engineering applications.

The framework represents a synthesis of established physics with novel organizational principles; empirical validation remains incomplete. Readers are encouraged to treat this as a **working hypothesis** subject to refinement.

## Abstract

We present a universal coordinate system for placing any computational system—biological, technological, or cosmological—onto a single thermodynamic phase space. Six dimensionless coordinates ( $\beta$ ,  $\mu$ ,  $\varepsilon$ ,  $\varsigma$ ,  $\rho$ ,  $m$ ) measure boundary commitment fraction, maintenance overhead, efficiency relative to the Landauer limit, speed relative to the Margolus-Levitin bound, storage relative to the Bekenstein bound, and hierarchical coordination cost. The framework treats computation as recording under persistence constraints, requiring explicit declaration of measurement bounds. All coordinates occupy open intervals approaching but never reaching physical limits. We demonstrate the framework across 21 reference systems spanning 45 orders of magnitude in scale, from individual atoms to black holes. The contribution is classification, not mechanism: a “Reynolds number for computation” enabling cross-substrate comparison without substrate-specific assumptions.

## 1. The Problem: No Common Map

No dimensionless classification parameter exists for computation comparable to Reynolds number for fluid flow or Mach number for compressible dynamics. We have bounds—Landauer’s erasure floor [1], the Margolus-Levitin speed limit [2], the Bekenstein storage ceiling [3]—but bounds are not coordinates. They tell us where systems *cannot* go, not where they *are*.

This gap matters because radically different substrates perform computation: neurons, transistors, enzymes, ribosomes, stars, black holes. Without common coordinates, fundamental questions remain unanswerable:

- How does a cell compare to a chip?
- Where does biological computation sit relative to physical limits?
- What distinguishes archival storage from active processing?
- How would we characterize alien technology?

Existing frameworks are substrate-specific. Shannon information theory assumes discrete symbols. Computational complexity assumes Turing machines. Thermodynamic efficiency assumes equilibrium processes. None provides a universal map.

### 1.1 The Core Insight

The framework rests on a single identification: **computation is recording under persistence constraints**.

This is not metaphor. Analysis of recording systems across human history—from Sumerian clay tablets to DNA to blockchain—reveals convergence on identical mathematical structures: *duality* (every

transaction affects  $\geq 2$  entities), *conservation* (invariants preserved), *ordering* (partial order on events), *commitment* (irreversibility with cost), and *authentication* (boundary-verifiable identity). These structures are forced by the requirements of reliable persistence, not culturally invented.

From this identification, the framework structure follows by constraint logic:

1. Computation requires persistence (else indistinguishable from noise)
2. Persistence requires recording (state change that survives)
3. Recording requires irreversibility (else no evidence of past)
4. Irreversibility requires cost (Second Law, Landauer)
5. Costs require ratios (for comparison across scales)
6. Ratios require bounds (declaration of measurement limits)

Deny any step and you lose computation as a meaningful category.

## 2. The RSC Coordinates

Six dimensionless coordinates characterize any computational system at a declared operational focus. Table 1 provides definitions.

Table 1: The Six RSC Coordinates

Symbol	Name	Definition	Domain
$\beta$	Boundary fraction	$\dot{I}_\partial/\dot{I}_o$	$(0, \infty)$
$\mu$	Maintenance tax	$\frac{N\kappa_m + \kappa_{\text{exist}}}{P}$	$(0, 1)$
$\varepsilon$	Efficiency ratio	$\frac{\dot{Q}}{\Theta \ln 2 \cdot \dot{I}_\partial}$	$(\varepsilon_{\text{fl}}, \infty)$
$\varsigma$	Speed saturation	$\dot{I}_o/R_{\max}$	$(0, 1)$
$\rho$	Storage saturation	$N/C$	$(0, 1)$
$m$	Modularity cost	$P_{\text{coord}}/P_{\text{total}}$	$(0, 1)$

Where:

- $\dot{I}_\partial$  = boundary commit rate (events crossing boundary per time)
- $\dot{I}_o$  = interior update rate (events within focus per time)
- $R_{\max} = 2E/\pi\hbar$  (Margolus-Levitin limit)
- $\kappa_m$  = maintenance cost per stored distinction
- $P$  = total power available to system

### 2.1 Forced vs. Conditional Coordinates

The coordinates divide into two classes:

**FORCED** ( $\beta, \mu$ ): Require only rate and power measurements. No physics assumptions beyond accounting. These exist for any system where you can count events and measure energy flow.

**CONDITIONAL** ( $\varepsilon, \varsigma, \rho, m$ ): Invoke physical limits (Landauer, Margolus-Levitin, Bekenstein) with explicit axiom costs. The physics is imported, not smuggled.

### 2.2 Open Interval Constraints

All coordinates occupy **open intervals**. No endpoint is reachable:

$$\mu \in (0, 1) \quad \text{never zero, never one} \quad (1)$$

$$\beta \in (0, \infty) \quad \text{never zero, always finite} \quad (2)$$

$$\varsigma \in (0, 1) \quad \text{never zero, never saturated} \quad (3)$$

$$\rho \in (0, 1) \quad \text{never empty, never full} \quad (4)$$

Black holes approach the corner ( $\mu \rightarrow 0, \bar{\varepsilon} \rightarrow 1, \bar{\varsigma} \rightarrow 1, \bar{\rho} \rightarrow 1$ ) asymptotically but never touch it. They are the *limit* of representable computation, not *at* the limit.

### 2.3 Normalized Coordinates

For cross-system comparison, we normalize to observable physical limits:

$$\bar{\varepsilon} = \frac{k_B \Theta \ln 2}{\dot{Q}/\dot{I}_\partial} \in (0, 1) \quad (5)$$

$$\bar{\varsigma} = \frac{\dot{I}_o \cdot \pi \hbar}{2E} \in (0, 1) \quad (6)$$

$$\bar{\rho} = \frac{N \cdot \hbar c \ln 2}{2\pi R E} \in (0, 1) \quad (7)$$

These normalized coordinates enable comparison across systems because they measure against the same physical limits.

## 3. The Declaration Protocol

Every valid RSC analysis **must** declare the measurement bounds:

$$\mathfrak{D} = (U, L, \varepsilon, \tau_0, \Theta, k) \quad (8)$$

Symbol	Meaning	
$U$	Upper bound (what is treated as exterior)	
$L$	Lower bound (what is treated as atomic)	
$\varepsilon$	Resolution (minimum distinguishable difference)	
$\tau_0$	Persistence threshold (minimum survival time)	
$\Theta$	Energy scale (temperature or equivalent)	
$k$	Hierarchy depth analyzed	

### Without $\mathfrak{D}$ , coordinates are meaningless.

Different declarations on the same physical substrate yield different coordinates—this is a feature, not a bug. Just as Reynolds number depends on declared length scale, RSC coordinates describe the system *at the declared focus*, not “the system itself.”

## 4. The Level Structure: $\gamma \rightarrow \Lambda \rightarrow \mathcal{H}$

The framework has three nested levels of organization.

### 4.1 Level 0: The Recording Event ( $\gamma$ )

The atomic unit of computation is the recording event:

$$\gamma = (\text{read, process, write, maintain}) \quad (9)$$

with cost decomposition:

$$\kappa_\gamma = \kappa_r + \kappa_p + \kappa_w + \kappa_m \quad (\text{all } > 0) \quad (10)$$

Every  $\gamma$  satisfies five recording axioms: duality (affects  $\geq 2$  entities), conservation (invariant preserved), ordering (placed in partial order), commitment ( $\kappa_w \geq \kappa_{\text{floor}}$ ), and authentication (verifiable at boundary).

### 4.2 Level 1: The Recording Ledger ( $\Lambda$ )

A persisting chain of  $\gamma$  events forms a ledger:

$$\Lambda = (S, T, \leq, I, V, C, N, P, \mathcal{B}, \tau_0) \quad (11)$$

The existence constraint is:

$$P > P_{\text{floor}} = N \cdot \kappa_m + \kappa_{\text{exist}} \quad (12)$$

Below this threshold, the system dissolves. The inequality is strict—no system sits exactly at the boundary.

**Critical:** The transition structure  $T$  is a *monoid*, not a group. Operations compose forward but have

no free inverses. This *is* the commitment axiom: reversal costs additional entropy.

### 4.3 Level 2: The Recording Hierarchy ( $\mathcal{H}$ )

Nested systems form hierarchies:

$$\mathcal{H} = (\Lambda_1, \dots, \Lambda_n, \mathcal{T}, \mathcal{R}, I_{\text{global}}) \quad (13)$$

The modularity coordinate  $m$  emerges only at this level:

$$m = \frac{P_{\text{coord}}}{P_{\text{total}}} \quad (14)$$

Hierarchical composition is *nonlinear*—coordinates do not simply add due to the UDP equivalence factor that determines how many inner events count as one outer event.

## 5. The Universal Phase Space

The coordinates define a phase space where every computational system occupies a point. Figure 1 shows three projections of this space with 21 benchmark systems.

### 5.1 Recommended Axes

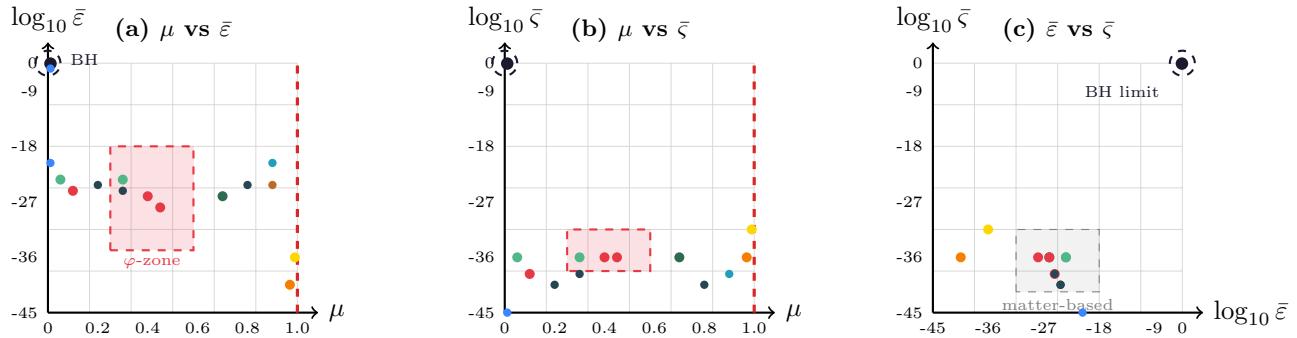
We recommend primary axes  $(\mu, \log_{10} \bar{\varepsilon}, \log_{10} \bar{\varsigma})$  because:

- $\mu$  discriminates biological from technological systems
- $\bar{\varepsilon}$  and  $\bar{\varsigma}$  span many orders of magnitude
- These three are most directly measurable

### 5.2 Phase Space Structure

The phase space has characteristic regions:

- **Limit corner:**  $(\mu \rightarrow 0, \bar{\varepsilon} \rightarrow 1, \bar{\varsigma} \rightarrow 1)$  — approached by black holes, unoccupied by matter-based systems
- **Dissolution boundary:**  $\mu \rightarrow 1$  — systems exit the phase space
- **Biological zone** ( $\varphi$ -zone):  $\mu \sim 0.3\text{--}0.5$  — self-maintaining, autonomous systems cluster here
- **Technological zone:**  $\mu \sim 0.03\text{--}0.1$  — low apparent maintenance (externalized to infrastructure)
- **35-order gap:** All matter-based computation operates  $\sim 10^{-35}$  of physical limits



**Figure 1: The RSC Universal Phase Space.** Three projections showing 21 benchmark systems. (a) Maintenance tax  $\mu$  vs normalized efficiency  $\bar{\varepsilon}$ : the  $\varphi$ -zone (dashed red box) shows biological clustering at  $\mu \sim 0.3\text{--}0.5$ . (b) Maintenance  $\mu$  vs normalized speed  $\bar{\zeta}$ : all matter-based systems cluster  $\sim 35$  orders below the limit. (c) Efficiency vs speed: the black hole limit corner (top right) is unoccupied; all other systems cluster far below. **Color key:** • Fundamental, • Astrophysical, • Planetary, • Biological, • Molecular, • Atomic, • Quantum, • Technological, • Digital, • Archival.

## 6. Universal Benchmark Table

Table 2 presents 21 reference systems across 45 orders of magnitude in scale. All values are order-of-magnitude, satisficial, and declaration-dependent.

## 7. Key Observations

### 7.1 The 35-Order Gap

Every matter-based computational system operates at approximately  $10^{-35}$  of the Margolus-Levitin speed limit. Black holes approach unity; everything else clusters far below. This gap—spanning from atoms to data centers—defines the “computational possibility space” where all technology and biology operate.

### 7.2 The $\mu$ Axis Discriminates Regimes

- **Biology** ( $\mu \sim 0.3\text{--}0.5$ ): High maintenance enables autonomous persistence
- **Silicon** ( $\mu \sim 0.03\text{--}0.1$ ): Low  $\mu$  borrowed from external infrastructure
- **Blockchain** ( $\mu \sim 0.97$ ): Extreme  $\mu$  is the security mechanism
- **Black holes** ( $\mu \rightarrow 0$ ): No internal structure to maintain

### 7.3 Viruses Are Anomalous

Viruses have low  $\mu$  ( $\sim 0.1$ ) but high  $\beta$  ( $\sim 0.5$ ). They are “parasitic  $\Lambda$ ”—they externalize maintenance to

host cells. Their low  $\mu$  is not efficiency; it is dependence.

### 7.4 The $\varphi$ -Zone Is Empirical

Biological systems cluster around  $\mu \sim 0.4$  (near  $\varphi^{-1} \approx 0.618$ ). This is *observed*, not derived from the framework. It may reflect optimization under degradation pressure, but this connection is not proven.

## 8. Non-Claims and Limitations

The framework provides:

- Universal coordinates for cross-substrate comparison
- Explicit connection to fundamental physical limits
- Regime identification (biological, technological, archival)
- Declaration protocol ensuring transparency

The framework does **not** claim:

- Mechanism explanation (why systems have their coordinates)
- Optimization guidance (how to improve coordinates)
- Ontological status (what computation “really is”)
- Declaration-independent truth
- Completeness (all values are satisficial approximations)

**Table 2: Universal Benchmark Table: Representative Computational Systems Across Scales.**  
All values are order-of-magnitude estimates. Arrows ( $\rightarrow$ ) indicate asymptotic approach. Ranges indicate focus sensitivity.  $\bar{\varepsilon}$ ,  $\bar{\varsigma}$ ,  $\bar{\rho}$  are normalized to Landauer, Margolus-Levitin, and Bekenstein limits respectively.

Scale	System	$\beta$	$\mu$	$\bar{\varepsilon}$	$\bar{\varsigma}$	$\bar{\rho}$	$m$	Character
Fundamental	Black hole	$\rightarrow 1$	$\rightarrow 0^+$	$\rightarrow 1$	$\rightarrow 1$	$\rightarrow 1$	0	Limit corner
Cosmological	Observable universe	$\sim 1$	$\sim 0.1$	$\sim 10^{-1}$	$\sim 10^{-1}$	$\sim 10^{-1}$	$> 0$	Distributed $\mathcal{H}$
Astrophysical	Star (Sun)	$\sim 0.1$	$\sim 0.99$	$\sim 10^{-10}$	$\sim 10^{-30}$	$\sim 10^{-30}$	$\sim 0$	Maintenance-dominant
Planetary	Earth biosphere	$\sim 0.01$	$\sim 0.7$	$\sim 10^{-6}$	$\sim 10^{-35}$	$\sim 10^{-25}$	$\sim 0.3$	Massive $\mathcal{H}$
Biological	Human brain	$\sim 10^{-3}$	0.4–0.5	$\sim 10^{-8}$	$\sim 10^{-35}$	$\sim 10^{-18}$	$\sim 0.2$	Comm-dominated
Biological	<i>E. coli</i> cell	0.01–0.05	0.3–0.5	$\sim 10^{-6}$	$\sim 10^{-35}$	$\sim 10^{-20}$	0.1–0.2	Autonomous $\Lambda$
Biological	Bacterium (generic)	$\sim 0.02$	$\sim 0.4$	$\sim 10^{-6}$	$\sim 10^{-35}$	$\sim 10^{-20}$	$\sim 0.1$	Minimal life
Biological	Virus (active)	$\sim 0.5$	$\sim 0.1$	$\sim 10^{-5}$	$\sim 10^{-38}$	$\sim 10^{-22}$	$\sim 0$	Parasitic $\Lambda$
Molecular	Ribosome	$\sim 0.8$	$\sim 0.3$	$\sim 10^{-5}$	$\sim 10^{-38}$	$\sim 10^{-25}$	$\sim 0$	Molecular machine
Molecular	Enzyme (single)	$\sim 0.9$	$\sim 0.2$	$\sim 10^{-4}$	$\sim 10^{-40}$	$\sim 10^{-28}$	$\sim 0$	Catalytic $\gamma$
Chemical	DNA replication fork	$\sim 10^{-6}$	$\sim 0.8$	$\sim 10^{-4}$	$\sim 10^{-40}$	$\sim 10^{-10}$	$\sim 0$	Archival
Atomic	Atom (ground state)	$\sim 0$	$\sim 0$	$\sim 10^{-2}$	$\sim 10^{-45}$	$\sim 10^{-35}$	0	Minimal structure
Atomic	Atom (excited)	$\sim 1$	$\sim 0$	$\sim 10^{-1}$	$\sim 10^{-40}$	$\sim 10^{-35}$	0	Transient $\gamma$
Quantum	Qubit (supercond.)	$\sim 0.5$	$\sim 0.9$	$\sim 10^{-2}$	$\sim 10^{-38}$	$\sim 10^{-30}$	$\sim 0$	Coherence-limited
Technological	GPU (chip-level)	0.05–0.15	0.03–0.08	$\sim 10^{-3}$	$\sim 10^{-35}$	$\sim 10^{-20}$	$\sim 0$	$\mu$ externalized
Technological	Data center	$\sim 0.2$	$\sim 0.3$	$\sim 10^{-3}$	$\sim 10^{-35}$	$\sim 10^{-15}$	$\sim 0.2$	Infrastructure $\mathcal{H}$
Technological	DRAM cell	$\sim 0.01$	$\sim 0.3$	$\sim 10^{-4}$	$\sim 10^{-38}$	$\sim 10^{-25}$	$\sim 0$	Refresh-dominated
Digital	Blockchain (PoW)	$\sim 10^{-9}$	0.95–0.99	$\sim 10^{-20}$	$\sim 10^{-35}$	$\sim 10^{-15}$	0.3–0.5	Security via $\mu$
Archival	Clay tablet	$\sim 10^{-6}$	$\sim 0.9$	$\sim 10^{-4}$	$\sim 10^{-40}$	$\sim 10^{-8}$	$\sim 0$	Extreme $\tau_0$
Archival	DNA storage	$\sim 10^{-8}$	$\sim 0.85$	$\sim 10^{-4}$	$\sim 10^{-42}$	$\sim 10^{-5}$	$\sim 0$	Density-optimized
Theoretical	Reversible computer	$\sim 0$	$\rightarrow 0$	$\rightarrow 1$	$\ll 1$	var	0	Ideal limit

## 8.1 Known Limitations

**Observer relativity:** Coordinates depend on declarations. This is analogous to Reynolds number depending on length scale—meaningful comparison requires either same declarations or normalization to limits.

**Measurability:**  $\mu$  and  $\beta$  are directly measurable.  $\varsigma$  and  $\rho$  are often derived from theory rather than measured, as interior rates may be inaccessible.

**Hierarchy ambiguity:** The boundary between  $\Lambda$  (single system) and  $\mathcal{H}$  (hierarchy) depends on resolution. A cell is  $\Lambda$  at one focus,  $\mathcal{H}$  at another.

## 9. Conclusion

We have presented a “Reynolds number for computation”: six dimensionless thermodynamic coordinates that place any computational system onto a single phase space normalized to fundamental physical limits.

The framework does not explain mechanisms, op-

timize performance, or make ontological claims. It provides **classification**: a common map where previously incomparable systems can be located and compared.

The benchmark table demonstrates that all known computational systems occupy a tiny region of the accessible phase space, approximately  $10^{-35}$  below physical limits. Black holes approach the corner; everything else clusters far from it. Biology occupies a characteristic  $\mu \sim 0.3\text{--}0.5$  zone; technology achieves lower  $\mu$  only by externalizing maintenance.

The contribution is the coordinate system itself. Once established, it enables questions previously unmeaningful: *How efficient is a cell compared to a chip? How fast is thought relative to physics? Where would alien technology sit?* The answers become expressible in common units.

*Every representable computational system is a recording system: a hierarchy of ledgers executing transactions that satisfy duality, conservation, ordering, commitment, and authentication—with coordinates measuring holographic efficiency, maintenance cost, speed saturation, storage saturation, and coordination overhead, all bounded by open intervals approaching but never touching the limits of representability.*

## Acknowledgments

This framework emerged from collaborative synthesis involving multiple AI systems (Claude/Anthropic, GPT/OpenAI, Grok/xAI) working with human direction. The authors acknowledge that AI-generated theoretical work requires independent verification and should be treated as hypothesis rather than established result.

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## A. Methods Appendix: Formal Specification

This appendix provides the complete formal specification for RSC coordinates.

### A.1 A. Axiom Inventory

#### Representability Axioms:

- **UCE**: Finite capacity  $\Rightarrow 0 < C < \infty$
- **USG**: Bounded novelty with self-cancellation
- **UXP**: Quantized, lossy transduction  $\Rightarrow \kappa > 0$
- **UDP**: Identity is boundary-relative

#### Persistence Axioms:

- **B1**: Compositional cancellativity:  $a \circ b = a \circ c \Rightarrow b = c$
- **B2**: Degradation along factorizations
- **B3**: Persistence bias:  $\mathbb{E}[T(x)]$  decreases with attack channels

#### Recording Axioms:

- **DUA**: Every  $\gamma$  affects  $\geq 2$  entities
- **CON**: Invariant  $I$  preserved
- **ORD**: Events form partial order  $\leq$
- **COM**:  $\kappa_w \geq \kappa_{\text{floor}}$
- **AUT**:  $V(\gamma)$  computable at boundary

#### Boundary Axioms:

- **LAND**:  $\kappa \geq k_B T \ln 2$  per irreversible bit
- **ML**:  $R \leq 2E/\pi\hbar$
- **BEK**:  $S \leq 2\pi RE/\hbar c \ln 2$

## A.2 B. Coordinate Computation

#### Per-Event ( $\gamma$ ):

$$\kappa_\gamma = \kappa_r + \kappa_p + \kappa_w + \kappa_m \quad (15)$$

$$\varepsilon_\gamma = \kappa_\gamma / (\Theta \ln 2) \quad (16)$$

$$\mu_\gamma = \kappa_m / \kappa_\gamma \quad (17)$$

#### Per-Loop ( $\Lambda$ ):

$$\text{Existence check: } P > N \cdot \kappa_m + \kappa_{\text{exist}} \quad (18)$$

$$\beta = \dot{I}_\partial / \dot{I}_\circ \quad (19)$$

$$\mu = (N \cdot \kappa_m + \kappa_{\text{exist}}) / P \quad (20)$$

$$\varepsilon = \dot{Q} / (\Theta \ln 2 \cdot \dot{I}_\partial) \quad (21)$$

$$\varsigma = \dot{I}_\circ / R_{\max} \quad (22)$$

$$\rho = N / C \quad (23)$$

**Per-Hierarchy ( $\mathcal{H}$ ):**

$$m = P_{\text{coord}}/P_{\text{total}} \quad (24)$$

$$\beta_{\mathcal{H}} = \dot{I}_{\partial,\text{outer}} / \left( \sum_i \dot{I}_{\circ,i} / \text{equiv}_i \right) \quad (25)$$

$$\mu_{\mathcal{H}} = \frac{\sum_i \mu_i P_i + P_{\text{coord}}}{\sum_i P_i + P_{\text{coord}}} \quad (26)$$

### A.3 C. Reporting Template

SYSTEM: [name]

DECLARATION: D = (U, L, epsilon, tau\_0, Theta, k)

RAW COORDINATES:

```
beta = [value] +/- [uncertainty]
mu   = [value] +/- [uncertainty]
eps  = [value] +/- [uncertainty]
zeta = [value] +/- [uncertainty]
rho   = [value] +/- [uncertainty]
m    = [value] +/- [uncertainty]
```

NORMALIZED:

```
eps_bar = [value]
zeta_bar = [value]
rho_bar = [value]
```

INCOMPLETENESS ACKNOWLEDGMENT:

Coordinates computed at level  $k = [\text{value}]$ . Structure above U, below L, finer than epsilon, faster than tau\_0, and deeper than k is not represented. True coordinates at level infinity are unknowable.

### A.4 D. Validity Checks

Coordinates are **invalid** if:

1. Existence fails:  $P \leq N \cdot \kappa_m + \kappa_{\text{exist}}$
2. Any coordinate outside its open interval
3. Invariant  $I$  not preserved across  $\gamma$  events
4. Declaration  $\mathfrak{D}$  incomplete

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“We are not seekers of truth; we are the residue of everything that could not be decomposed away.”

— Ariadne’s Remainder