Metastable Information as a Physical Resource in Cyber-Physical Systems: Formalization and the Method of Demonstrable Information Physical Value (DIPV)

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Abstract

This paper introduces and explicitly formalizes, to the author's knowledge for the first time, the concept of *metastable information* as a physical resource in cyber-physical systems (CPS). Unlike classical treatments in the physics of information and the thermodynamics of computation [3, 2, 7], information is treated not merely as an abstract quantity or computational artifact, but as a physically instantiated structure whose *systemic destruction* (invalidation of operative consequences) can cost fundamentally more than its creation due to thermodynamic, structural, and institutional irreversibility.

Based on established physical principles—the Landauer bound [3], the Bekenstein bound [1], and system-level irreversibility arguments [2, 7]—we formalize metastable information via a measurable cost-asymmetry criterion. We propose the **Demonstrable Information Physical Value (DIPV)** method, combining physical irreversibility, structural metastability, cryptographic fixation, and institutional embedding. The work fixes priority in the stated formulation and provides a foundation for resilient CPS and socio-technical systems.

Keywords: physics of information; cyber-physical systems; metastability; Landauer principle; irreversibility; demonstrable information value; distributed systems; auditability.

1 Introduction

Information processing in cyber-physical systems (CPS) is unavoidably physical. Storage, transmission, and computation are implemented through physical states and therefore obey thermodynamic constraints. This becomes operationally important when information is expected to carry value, authority, and real-world consequences within a system.

The Landauer principle establishes a lower bound on energy dissipation required for irreversible erasure of information [3]. Bennett clarified that reversible computation can, in principle, reduce dissipation, but practical systems reintroduce irreversibility due to finite memory, noise, and structural overhead [2]. The Bekenstein bound limits the maximum information content in a finite region with given energy and size [1]. Zurek's analysis ties information and entropy production to physical constraints [7].

Despite extensive prior work, the literature lacks an explicit CPS-oriented formalization that treats information as a metastable physical resource characterized by strong creation–destruction cost asymmetry. This paper addresses that gap.

2 Related Work (Positioning and Distinctions)

Thermodynamics of computation and information physics. Landauer established the physical cost of irreversible operations [3], and Bennett explored reversibility and its trade-offs [2]. Zurek connected information to entropy production and classical emergence [7]. These works provide fundamental constraints but do not offer a CPS-level concept of *systemic invalidation cost* as a primary driver of information value.

Bounds on information in physical systems. Bekenstein's bound constrains maximal information content in finite regions [1]. This work uses the general implication that information is physically resource-limited to motivate enforceable value through system design.

Distributed records and auditability. Many systems employ redundancy, anchoring, and audit logs. The novelty claimed here is not the use of any single mechanism, but the explicit unification of physical irreversibility, structural metastability, and institutional embedding into a formal criterion and method (DIPV) targeting *invalidation of consequences*, not merely deletion of copies.

3 Physical Foundations

3.1 Landauer bound and irreversibility

The minimal heat dissipated when erasing one bit is bounded as:

$$Q \geq k_B T \ln 2. \tag{1}$$

This provides a universal physical floor for logically irreversible erasure [3].

3.2 Finite resources: Bekenstein bound

The Bekenstein bound limits information capacity in finite physical systems [1].

3.3 System-level irreversibility

Even if individual operations are optimized, practical systems reintroduce irreversibility due to finite memory, noise, and overhead [2, 7]. This motivates enforcing value by making invalidation expensive.

4 Formal Definition of Metastable Information

Definition 1 (Metastable Information). Metastable information is information instantiated in physical or cyber-physical states separated by energetic, structural, or systemic barriers such that the expected cost of complete destruction or invalidation significantly exceeds the cost of creation.

Cost notion. Cost includes energy, time, computation, coordination, consensus, and institutional/procedural resources required to reach a state equivalent to the absence of the information and its operative consequences.

5 Creation–Destruction Asymmetry

We formalize the core claim as:

$$C_{\text{destroy}} \gg C_{\text{create}}. \tag{2}$$

6 The DIPV Method

Definition 2 (DIPV). The Demonstrable Information Physical Value (DIPV) method is a reproducible design procedure that enforces information value through: (i) physical irreversibility, (ii) structural metastability, (iii) systemic fixation, and (iv) cryptographic fixation.

6.1 Procedure (high-level steps)

1. Object structuring: canonical representation of the information object.
2. Cryptographic commitment: hash and, optionally, signature.
3. Independent anchoring: place commitments in one or more independent verification contexts.
4. Process binding: bind the object to operational or decision-making processes.
5. Auditability: maintain traceability of use, updates, and invalidations.
6. Acceptance rule: treat an object as valid only if proofs satisfy policy.

6.2 Algorithmic pseudocode

Algorithm 1 DIPV: construction of a demonstrably valuable information object

Require: content m, metadata/context ctx, verification policy P
Ensure: object X with proof package $Proof$

$x \leftarrow \text{Normalize}(m, ctx)$
$h \leftarrow \text{Hash}(x)$
$sig \leftarrow \text{Sign}(h, sk)$
$anchor \leftarrow \text{Anchor}(h, sig, P)$
$deps \leftarrow \text{BindToProcess}(x, P)$
$AuditTrail \leftarrow \text{InitTrail}(h, anchor, deps)$
$Proof \leftarrow \{h, sig, anchor, AuditTrail\}$
$X \leftarrow \{x, Proof\}$
return $(X, Proof)$

7 Threat Model

Demonstrability is interpreted engineering-wise: verifiable within an explicit threat model. We assume standard cryptographic security, at least one independent verification anchor remains accessible, and compromising all anchors is substantially more expensive than creation.

8 Security Considerations and Attack Cost Discussion

The threat model maps to systemic invalidation cost decomposition (Appendix A, Eq. 3). DIPV shifts the target from "delete a copy" to "invalidate consequences", increasing attack cost via coordination, consensus, and institutional components.

9 Tables and Illustrative Plots

9.1 Tables

Table 1: Information classes and relative destruction cost (qualitative)

Information class	Carrier	Distribution	Creation	Destruction
Local record	local medium	low	low	low
Centralized DB record	server/DC	medium	medium	medium
Distributed fixation	multi-node network	high	medium	high
Legally significant record	law + infra	high	medium	very high

Table 2: Factors increasing destruction/invalidation cost

Factor	Effect
Metastability	raises barriers; increases required work
Distribution	requires coordination across participants/nodes
Coupling/Dependencies	forces correction of downstream consequences
Institutional embedding	adds procedural and legal irreversibility

Table 3: Landauer minimal energy for erasing 1 bit, $E_{\min} = k_B T \ln 2$ (order-of-magnitude)

Temperature (K)	$E_{\min}$ (J)	Note
300	$\approx 2.9 \times 10^{-21}$	room temperature
77	$\approx 7.4 \times 10^{-22}$	liquid nitrogen
4	$\approx 3.8 \times 10^{-23}$	cryogenic regime

9.2 Plots (pgfplots)

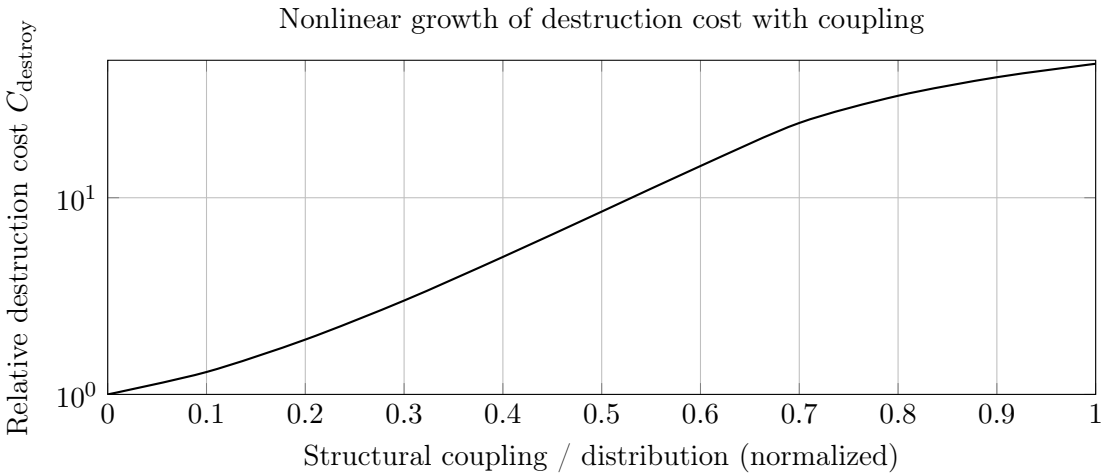

Figure 1: Illustrative plot: qualitative growth of C_{destroy} with distribution and coupling.

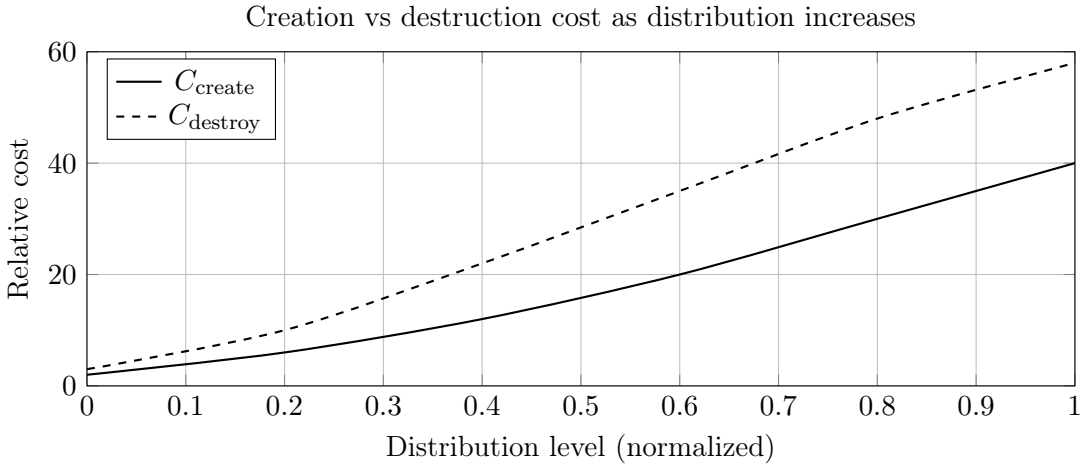

Figure 2: Illustrative plot: destruction/invalidation cost can increase faster than creation cost.

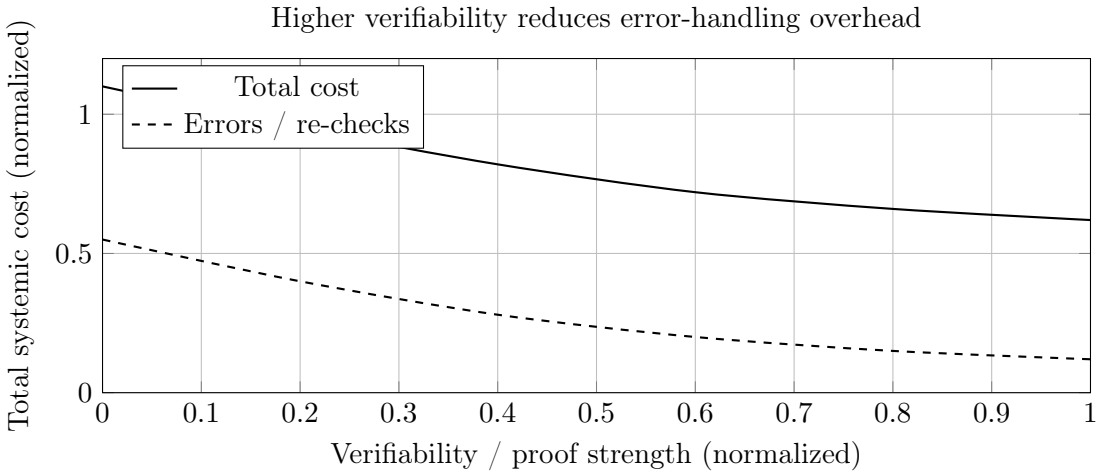

Figure 3: Illustrative plot: stronger proofs reduce costs spent on disputes and re-checks.

10 Discussion and Limitations

The novelty is the explicit unification of physical irreversibility, structural metastability, cryptographic fixation, and institutional embedding into a cost criterion and a reproducible method targeting systemic invalidation of consequences.

Limitations: plots are illustrative; cost components are context-dependent; demonstrability is defined under a threat model; legal effects vary by jurisdiction.

11 Conclusion

We introduced metastable information as a CPS resource, formalized creation–destruction cost asymmetry, and proposed DIPV with threat modeling and cost-based security interpretation.

Prior Work by the Author

Earlier materials by the author are available in open access form [4, 5, 6]. The present work provides unified formalization and the DIPV method.

A Appendix A. Formal Cost Model of Destruction/Invalidation

Let x be an information object within system S. Define:

$$C_{\text{destroy}}(x;S) = C_{\text{phys}}(x) + C_{\text{comp}}(x;S) + C_{\text{coord}}(x;S) + C_{\text{cons}}(x;S) + C_{\text{inst}}(x;S). \tag{3}$$

Metastability holds if:

$$\frac{C_{\text{destroy}}(x;S)}{C_{\text{create}}(x;S)} \geq \Gamma, \qquad \Gamma \gg 1. \tag{4}$$

B Appendix B. Deletion vs Invalidation and Practical Verifiability

Deletion removes a specific copy in a specific storage. **Invalidation** makes the object unacceptable as valid and neutralizes dependencies.

Engineering criteria for strong evidence: integrity, origin, time/order fixation, traceability, independent verification.

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Patent-Oriented Disclosure and Reservation of Rights

The author discloses herein an original conceptual framework, formal definitions, and a method referred to as **Demonstrable Information Physical Value (DIPV)**, including the concept of metastable information as a physical resource in cyber-physical systems.

This disclosure is made for the purposes of scientific communication, public verification, and the establishment of priority. Nothing in this publication shall be construed as a waiver, abandonment, or limitation of any present or future intellectual property rights, including but not limited to patent rights, that may arise from the concepts, methods, or implementations described herein.

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