Observer as a Finite Distinction Register: Measurement Capacity, Dynamic Bottlenecks, and Budget-Crossing Signatures

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A physical observer is often treated as an idealized point of access to facts. FDS-O1 replaces this abstraction with an operational definition: an observer is a finite distinction-register, namely a physical system that can register, preserve, update, order, and communicate distinctions only through finite records, finite channels, finite update rates, finite buffers, and finite thermodynamic budgets. Building on finite-observer distinguishability budgets, this paper formulates physical measurement as stable record formation under finite capacity. A measurement event is not merely an interaction; it is the stabilization of an accessible record whose distinction class can be retained and used by a finite observer within a specified time window. We define measurement capacity through dynamically coupled bottlenecks: sensor resolution, readout channel, internal memory, record stability, buffering, externalized access, compression, and irreversible update throughput. We compare this accessible capacity with task-relevant rate-distortion demand. If demand exceeds capacity, full-fidelity measurement is operationally impossible: the observer must coarse-grain, merge states, increase latency, buffer, externalize records, reset memory, dissipate housekeeping heat through irreversible updates, relax the task, or fail. This version extends the minimal O1 model by adding dynamic resource allocation, transient versus sustained crossing, reversible-versus-irreversible heat accounting, a two-dimensional sensor-array simulation, an operational interface with decoherence, and a comparison with active inference. The paper does not derive quantum measurement, collapse, the Born rule, decoherence, the Bekenstein bound, holography, or the Einstein equations. Its contribution is narrower: it converts finite-observer distinguishability budgets into a concrete measurement-diagnostics framework with explicit budget-crossing signatures.

Scope and Boundary of the Theory. This paper does not claim that consciousness is required for observation. It does not claim to solve the quantum measurement problem, derive the Born rule, replace decoherence theory, modify unitary quantum mechanics, or derive gravitational entropy bounds. It treats an observer as a finite physical record-bearing system. Its contribution is to define measurement capacity, dynamic bottleneck coupling, buffering, stable record formation, and budget-crossing signatures for such systems.

Claim-status summary

Table I summarizes the central FDS-O1 claims, their epistemic status, and the conditions under which they should be weakened or rejected.

Keywords: finite observer; measurement theory; distinction register; detector capacity; dynamic bottlenecks; buffering; finite records; rate-distortion; Landauer principle; reversible computation; information thermodynamics; budget crossing; sensor array; active inference; decoherence interface; active finite distinction systems.

INTRODUCTION

The operational observer problem

Physics routinely uses the word "observer" while leaving its physical implementation implicit. In some contexts the observer is a human, in others a detector, an apparatus, a memory register, a computational agent, a horizon-bounded exterior system, or an environment carrying records. The common operational feature is not consciousness. It is record-bearing distinction. Something happens that leaves a reproducible trace; that trace can be preserved, checked, updated, compared, communicated, and used.

FDS-T1 introduced finite distinguishability budgets for physical observers. It defined an observer-relative finite projection $\pi_{\mathcal{O}}$ and bit capacity $C_{\mathcal{O}} = \log_2 |\mathrm{Im}(\pi_{\mathcal{O}})|$, then treated accessible capacity as a bottleneck over finite memory, boundary access, readout channel, causal reach, external records, and irreversible update throughput [1]. The present paper turns that physical bridge into an operational measurement paper. It asks: when is a detector, instrument, apparatus, organism, robot, or laboratory system a finite distinction-register? What makes an interaction into a measurement? How do finite sensor resolution, channel capacity, buffering, record stability, memory reuse, and irreversible updates constrain what can be measured?

TABLE I. Central FDS-O1 claims, epistemic status, and demotion or failure conditions.

Claim	Status	What would weaken or falsify it
Observer as finite distinction-register	Operational bridge	A complete physical account of registered observations requiring no finite carrier, boundary, stability condition, readout, or update capacity
Measurement as stable record formation	Operational definition	Measurement outcomes used operationally without any stable record, reproducible trace, or accessible registration
Measurement capacity is dynamically bottlenecked	Conditional theorem	Full-fidelity measurement bypasses all sensor, channel, memory, record-stability, buffering, externalization, and update constraints
Budget crossing produces observable exits	Testable prediction	No change in error, latency, coarse-graining, state merging, externalization, reset, heat, or failure when demand crosses accessible measurement capacity
Buffers separate transient from sustained crossing	Engineering bridge	Finite buffers neither delay transient overload nor sharpen sustained overflow in controlled acquisition systems
Irreversible record reuse carries housekeeping cost	Physical bridge	Repeated logically irreversible record reuse below generalized Landauer accounting under stated thermodynamic conditions
Active inference depends on finite record formation	Interface claim	Inference and control are empirically invariant to severe record compression, delay, merging, and unavailable observations under otherwise matched tasks

Main thesis

The main thesis is:

$$\text{observer} = \text{finite distinction-register}, \tag{1}$$

not a disembodied point of knowledge. A measurement is the stabilization of at least one record distinction that remains accessible to such a finite register over a specified retention and verification window.

Let Ω be a physical possibility space for a source, region, or task. A finite observer implements a projection

$$\pi_{\mathcal{O}} : \Omega \to \mathcal{Z}_{\mathcal{O}}, \tag{2}$$

where $\mathcal{Z}_{\mathcal{O}}$ is the finite set of record classes that can be reliably distinguished by the observer. The measurement problem addressed here is not the quantum collapse problem. It is the finite-capacity problem:

$$R^{(\tau)}_{\min}(\varepsilon; \Psi) > C_{\text{meas}}(\mathcal{O}, \mathcal{D}, t, \tau). \tag{3}$$

When the task-relevant distinction demand exceeds the accessible measurement capacity, no protocol can produce full-fidelity stable records without changing the boundary, increasing time, using buffers, externalizing information, paying additional reset cost, or relaxing the task.

New contributions in v0.2

This version adds six components beyond the initial O1 draft.

1. **Dynamic bottleneck coupling:** capacity terms are no longer treated as independent constants; they arise from resource allocation and trade-offs.
2. **Buffering:** transient crossing can be absorbed, whereas sustained crossing causes buffer overflow and sharper signatures.
3. **Housekeeping heat separation:** reversible sensing and copying are distinguished from irreversible reset, overwrite, compression, and garbage collection.
4. **Two-dimensional sensor-array simulation:** a finite-capacity camera-like system shows false merging and ghosting under update limits.
5. **Decoherence interface:** O1 supplies an operational record criterion for when environmental information becomes accessible as a stable measurement record.
6. **Active inference interface:** O1 specifies the finite-record precondition under which an agent can even receive the observations used in variational free-energy minimization.

What is not claimed

This paper does not derive quantum mechanics, decoherence, the Born rule, the Bekenstein bound, holography, general relativity, or the Standard Model. It is compatible with standard unitary dynamics, standard decoherence theory, and ordinary detector physics. It does not claim that every physical interaction is a measurement. The additional condition is record stabilization under finite accessibility. The paper's purpose is narrower: to make observerhood and measurement capacity explicit finite-physical variables.

RELATED WORK

Operational and relational observers

Operational approaches emphasize that a measurement is an operation with a record. Wheeler's "it from bit" placed information and physical registration at the center of physical meaning [2]. Relational quantum mechanics treats states as relative to interacting systems rather than as observer-independent catalogues of facts [3]. QBist and operational approaches similarly stress that quantum-state assignments depend on the agent or experimental arrangement [4]. FDS-O1 is compatible with this operational tradition, but it is more restrictive: it asks what physical resources are required for the agent, detector, or apparatus to function as a finite distinction-register.

Decoherence and stable records

Decoherence theory explains the suppression of interference in open quantum systems and the emergence of stable pointer states under environment-induced superselection [5, 6]. Quantum Darwinism studies redundant environmental encoding of information that makes records objectively available to many observers [7]. FDS-O1 does not replace decoherence theory. It uses the language of stable record formation: a result is operationally classical when it can be registered, preserved, communicated, and cross-validated by finite observers.

Information theory, detector physics, and Landauer accounting

Shannon capacity and rate-distortion theory provide the natural language for comparing signal complexity to finite representation capacity [8–11]. Real detectors have finite resolution, dynamic range, bandwidth, dead time, noise temperature, memory, calibration stability, and readout constraints. FDS-O1 does not compete with instrument-specific physics. It supplies a cross-domain capacity ledger.

Landauer's principle gives a lower bound on heat dissipation for logically irreversible erasure under specified thermodynamic conditions [12]. Bennett emphasized that reversible computation can avoid local erasure cost while still requiring care about garbage and memory reuse [13]. Experimental tests have verified Landauer-style bounds in controlled settings [14–16]. FDS-O1 uses Landauer conservatively: the bridge is applied to irreversible record reset, overwrite, many-to-one compression, and garbage collection, not to every physical interaction or reversible sensing step.

Active inference and embodied measurement

Active inference treats perception and action as inference under a generative model, often expressed as minimization of variational free energy [22, 23]. Recent active-inference reviews frame action and perception as a unified process of prediction, inference, and control [24]. FDS-O1 does not replace active inference. It addresses a prior physical layer: the observation y_t used by an agent is itself a finite record. If record formation is capacity-limited, delayed, compressed, or merged, then inference operates on $\tilde{y}_t = \pi_{\mathcal{O}}(y_t)$ rather than on an ideal observation. This connects measurement capacity to robotics, embodied AI, biological sensing, and instrumentation.

FINITE-REGISTER MEASUREMENT MODEL

Definition 1 (Physical distinction). *A physical distinction is a difference between alternatives instantiated by a record, coupling, detector state, boundary condition, memory state, or other physical carrier. A formal partition without a physical carrier is not yet a measurement distinction.*

Definition 2 (Finite distinction projection). *Let Ω be a physical possibility space. A finite observer $\mathcal{O}$ implements a projection*

$$\pi_{\mathcal{O}} : \Omega \to \mathcal{Z}_{\mathcal{O}}, \tag{4}$$

where $\mathcal{Z}_{\mathcal{O}}$ is the set of accessible record classes. The observer's instantaneous distinguishability budget is

$$N_{\mathcal{O}} = |\operatorname{Im}(\pi_{\mathcal{O}})|, \qquad C_{\mathcal{O}} = \log_2 N_{\mathcal{O}}. \tag{5}$$

Definition 3 (Finite distinction-register). *A finite distinction-register is a physical system that can register, preserve, update, order, and communicate distinctions using finite resources. It must have a record carrier, a boundary or interface, a stability condition, a readout channel, and a finite update capacity.*

The term observer is used here only in this operational sense. A detector array, memory device, biological sensory system, robotic sensor, laboratory apparatus, or composite experimental system may count as an observer when it functions as a finite distinction-register.

Definition 4 (Measurement event)**.** *A measurement event for task family Ψ is a process that maps a physical possibility $\omega \in \Omega$ into a record class $z \in \mathcal{Z}_{\mathcal{O}}$ such that the record remains retrievable, orderable, and usable by $\mathcal{O}$ over a specified retention and verification window $[t, t+\tau]$ with error probability at most δ and distortion at most ε.*

Let M_t be the memory state carrying a record at time t. A record class z is stable over τ if

$$\mathbb{P}\left[\hat{z}(t+\tau) = z \mid M_t = z\right] \geq 1 - \delta. \tag{6}$$

The effective record-stability capacity $C_{\mathrm{rec}}(t, \tau)$ counts only distinctions satisfying this stability requirement.

DYNAMIC MEASUREMENT CAPACITY

From static bottleneck to coupled resource allocation

The simplest O1 capacity ledger writes

$$C_{\mathrm{meas}} = \min\{C_{\mathrm{sens}}, C_{\mathrm{chan}}, C_{\mathrm{mem}}, C_{\mathrm{rec}}, C^{\mathrm{eff}}_{\mathrm{ext}}, I^{\max}_{\mathrm{update}}\}. \tag{7}$$

This is useful as an accounting identity, but real systems do not hold these terms fixed. Increasing sensor sampling may increase inflow into memory. Compression can relieve a channel bottleneck while reducing record fidelity and consuming update capacity. Externalization can increase effective storage while increasing latency and verification overhead.

We therefore introduce a resource-allocation vector

$$\mathbf{r}(t) = (r_{\mathrm{sens}}, r_{\mathrm{chan}}, r_{\mathrm{mem}}, r_{\mathrm{rec}}, r_{\mathrm{comp}}, r_{\mathrm{ext}}), \tag{8}$$

subject to

$$\sum_i r_i(t) \leq R_{\mathrm{tot}}(t), \qquad r_i(t) \geq 0. \tag{9}$$

The capacity terms are functions of allocation, load, temperature, noise, and retention window:

$$C_i(t) = C_i\big(r_i(t), \Psi(t), T(t), B(t), \tau\big). \tag{10}$$

The coupled accessible capacity is still

$$C_{\mathrm{meas}}(t) = \min_i C_i(t), \tag{11}$$

but the active bottleneck can move because the capacities co-evolve.

Memory fill and compression feedback

Let $M(t)$ be memory or buffer occupancy. A generic acquisition balance is

$$\dot{M}(t) = I_{\mathrm{in}}(t) - I_{\mathrm{compress}}(t) - I_{\mathrm{ext}}(t) - I_{\mathrm{erase}}(t). \tag{12}$$

If $M(t)$ approaches $M_{\max}$, the observer must either increase compression, externalize, erase, lower sampling, increase latency, or fail. Compression creates a trade-off:

$$C^{\mathrm{eff}}_{\mathrm{chan}}(t) = C_{\mathrm{chan}}(t) + G_{\mathrm{comp}}(t), \tag{13}$$

$$C^{\mathrm{eff}}_{\mathrm{rec}}(t) = C_{\mathrm{rec}}(t) - L_{\mathrm{comp}}(t), \tag{14}$$

$$I^{\max,\mathrm{eff}}_{\mathrm{update}}(t) = I^{\max}_{\mathrm{update}}(t) - U_{\mathrm{comp}}(t). \tag{15}$$

The same intervention that relieves one bottleneck can activate another.

Measurement demand and capacity deficit

For a task family Ψ, distortion tolerance ε, and measurement window τ, let

$$R^{(\tau)}_{\min}(\varepsilon; \Psi) \tag{16}$$

be the minimal task-relevant bits required to meet the target error or distortion. The FDS-O1 measurement deficit is

$$\Delta_{\mathrm{O1}}(t) = R^{(\tau)}_{\min}(\varepsilon; \Psi_t) - C_{\mathrm{meas}}(t). \tag{17}$$

A positive deficit is not ordinary ignorance. It is an operational impossibility under the given boundary, detector, channel, memory, buffer, update, and stability constraints.

Theorem 1 (Finite measurement budget-exit theorem)**.** *Let $\mathcal{O}$ be a finite distinction-register coupled to measurement apparatus $\mathcal{D}$ for task family Ψ over $[t, t+\tau]$. If*

$$R^{(\tau)}_{\min}(\varepsilon; \Psi) > C_{\mathrm{meas}}(\mathcal{O}, \mathcal{D}, t, \tau), \tag{18}$$

then full-fidelity stable measurement at distortion ε is impossible unless at least one exit occurs: coarse-graining, state merging, increased latency or integration time, buffering, externalization, additional irreversible reset/garbage collection, task relaxation, boundary enlargement, or failure.

Proof. $R^{(\tau)}_{\min}(\varepsilon; \Psi)$ is the minimum task-relevant information required to meet the measurement target. C_{meas} is the maximum number of task-relevant distinctions the finite observer-apparatus system can register, stabilize, update, and use over the same window. If demand exceeds capacity, a full-fidelity record would require distinctions not carried by any admissible register state or update sequence. The system must therefore reduce demand, enlarge or alter capacity, store backlog in a finite buffer, externalize, pay additional irreversible updating cost, or fail. These alternatives exhaust the ways to remove the strict inequality under finite resources. □

The empirical content of the theorem is not the logical implication itself, but the predicted pattern of exits: bottleneck switching, latency discontinuities, buffer overflow, false merging, externalization bursts, reset cascades, and excess irreversible housekeeping costs should co-occur when independently estimated task demand crosses independently estimated accessible measurement capacity.

BUFFERING: TRANSIENT VS SUSTAINED CROSSING

Real instruments often survive short overloads by using buffers. Let $B_{\text{buf}}(t)$ be buffer occupancy and $B_{\text{buf}}^{\max}$ be buffer capacity. Define

$$\Delta_+(t) = \max\{\Delta_{\text{O1}}(t), 0\}. \tag{19}$$

A minimal buffer balance is

$$\dot{B}_{\text{buf}}(t) = \Delta_+(t) - D_{\text{drain}}(t), \qquad 0 \le B_{\text{buf}}(t) \le B_{\text{buf}}^{\max}. \tag{20}$$

Transient crossing can be absorbed if

$$\int_{t_0}^{t_1} \Delta_+(s)\, ds < B_{\text{buf}}^{\max} - B_{\text{buf}}(t_0) + \int_{t_0}^{t_1} D_{\text{drain}}(s)\, ds. \tag{21}$$

Sustained crossing occurs when the inequality is violated. Then the buffer overflows, and the exit signatures sharpen: state drops, false merging, hard latency jumps, reset cascades, externalization bursts, or failure. Buffering therefore does not eliminate budget crossing; it temporally reshapes it.

HOUSEKEEPING HEAT AND REVERSIBLE CONTROLS

The thermodynamic signature of FDS-O1 must be stated carefully. Total power contains many contributions:

$$P_{\text{total}} = P_{\text{sens}} + P_{\text{chan}} + P_{\text{control}} + P_{\text{storage}} + P_{\text{irr}}. \tag{22}$$

FDS-O1 does not claim that all of these are Landauer costs. The relevant term is irreversible housekeeping:

$$P_{\text{hk}} \ge k_{\text{B}} T \ln 2\, \dot{I}_{\text{erase}}, \tag{23}$$

where $\dot{I}_{\text{erase}}$ counts logically irreversible reset, overwrite, many-to-one compression, or garbage collection under the relevant thermodynamic assumptions.

Recent reviews of the Landauer principle emphasize that practical erasure generally dissipates more than the ideal bound, and that finite-time, finite-size-bath, nonequilibrium, non-Markovian, and quantum regimes require generalized accounting beyond the textbook single-bit limit [25].

Bennett-style reversible computation shows that sensing, copying, and computation can in principle be arranged to avoid local erasure, provided sufficient reversible memory and garbage management are available [13]. O1 therefore predicts not simply "more measurement implies more heat," but a sharper contrast. Fixed memory with repeated reuse should produce a higher immediate housekeeping-heat floor. Expanded memory with delayed erasure should lower immediate heat, but only by paying a storage, boundary, or later garbage-collection cost. This separation makes the heat signature experimentally interpretable.

Recent quantum many-body experiments have also probed generalized Landauer accounting in system-environment partitions, relating energy flow, entropy change, mutual information, and relative entropy in out-of-equilibrium quantum fields [26].

NUMERICAL MODELS AND SIMULATIONS

The simulations are deterministic synthetic demonstrations. They are not fits to physical detector data, quantum experiments, or human observations. They provide a reproducible diagnostic template for the O1 model. All figures and CSV outputs are generated by `code/generate_results.py`.

Dynamic bottleneck coupling

The first simulation increases scene complexity and lets the observer respond by increasing sampling and compression. Compression improves effective channel capacity but reduces record stability and update throughput. Memory fill accumulates when inflow exceeds processing and drain. Thus the active bottleneck changes dynamically rather than being a fixed independent minimum.

Buffering

The second simulation contrasts a short transient pulse with a sustained overload. A finite buffer absorbs the transient crossing, producing latency without failure. The sustained crossing fills the buffer and produces a sharper error/merge signature.

Housekeeping heat

The third simulation compares a fixed-memory observer that repeatedly overwrites records with an expanding-memory observer that delays erasure by allocating more physical storage. The fixed-memory system produces an earlier irreversible heat signature. The expanding-memory system lowers immediate heat but pays in boundary and storage cost.

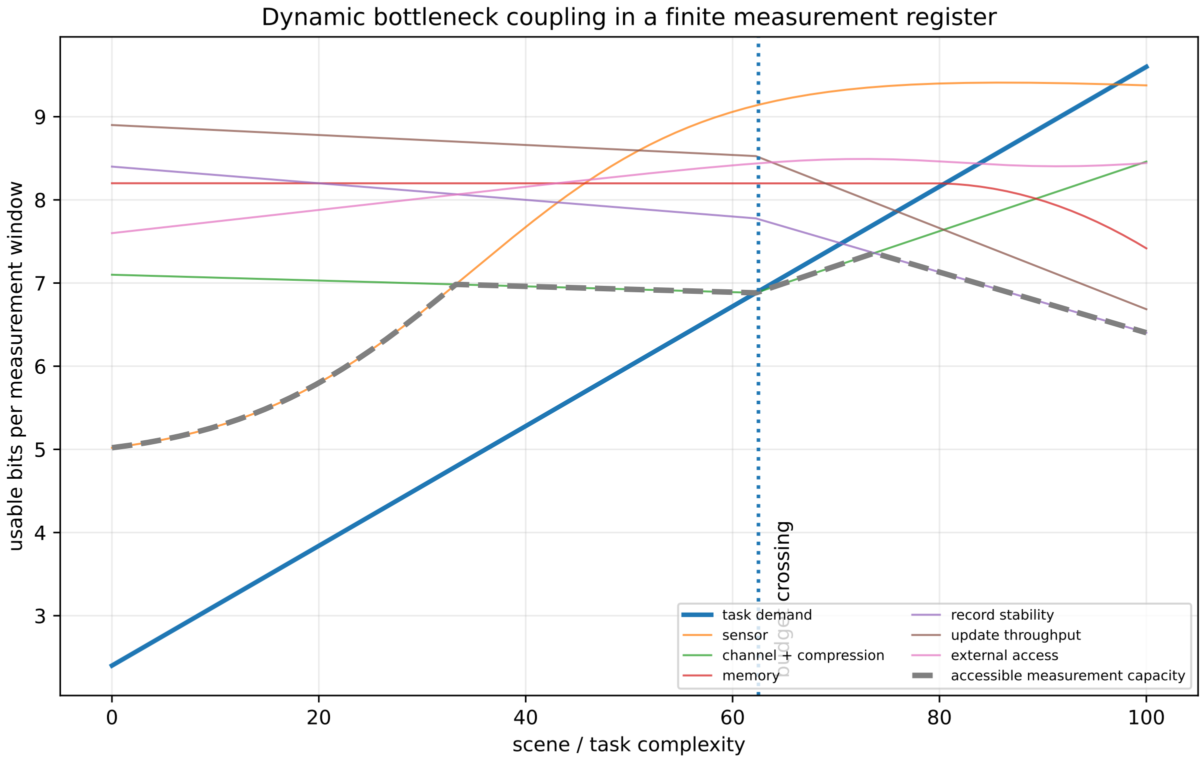

FIG. 1. Dynamic bottleneck coupling in a finite measurement register. Task demand rises with scene complexity. Sampling increases sensor capacity, compression partially relieves the channel, but compression and memory fill reduce record stability and update throughput. Accessible capacity is the lower envelope of dynamically coupled terms.

Two-dimensional sensor-array demonstration

The fourth simulation uses a finite-capacity camera-like array tracking multiple moving Gaussian objects. The high-capacity register preserves separate record classes. The low-capacity register uses coarse block averaging and delayed update, producing false merging and ghost persistence. This simulation illustrates how O1 signatures appear in a visually interpretable measurement task.

Decoherence-record interface

The fifth simulation is not a quantum derivation. It illustrates an operational interface: environmental branch information can grow on a decoherence timescale, but an observer obtains an operational measurement only when finite accessible record capacity crosses the task threshold and stabilizes the record. Different thresholds produce different record-formation times.

INTERFACE WITH DECOHERENCE

FDS-O1 is intentionally conservative about quantum foundations. It does not claim that finite distinction budgets collapse the wavefunction, derive the Born rule, or replace decoherence theory. It says instead that a quantum outcome becomes operationally available to a finite observer only when a stable record is produced.

Let S be a quantum system and E_t the environment after time t. Let $I_{\rm env}(S;E_t)$ denote information about the system state redundantly or effectively available in environmental degrees of freedom. Let $C^{\rm acc}_{\rm app}(t)$ be the apparatus-accessible record capacity. An O1-style operational record condition is

$$\min\{I_{\rm env}(S;E_t), C^{\rm acc}_{\rm app}(t), C_{\rm rec}(t,\tau)\} \geq R_{\rm min}(\varepsilon;S). \quad (24)$$

Define

$$\tau_{\rm rec} = \inf\{t : \min[I_{\rm env}(S;E_t), C^{\rm acc}_{\rm app}(t), C_{\rm rec}(t,\tau)] \geq R_{\rm min}(\varepsilon;S)\}. \quad (25)$$

The comparison between $\tau_{\rm rec}$ and the usual decoherence time τ_d is an empirical and model-dependent matter. FDS-O1 does not require equality. It requires only that decoherence-like environmental information becomes an operational measurement for a finite observer through accessible stable record formation.

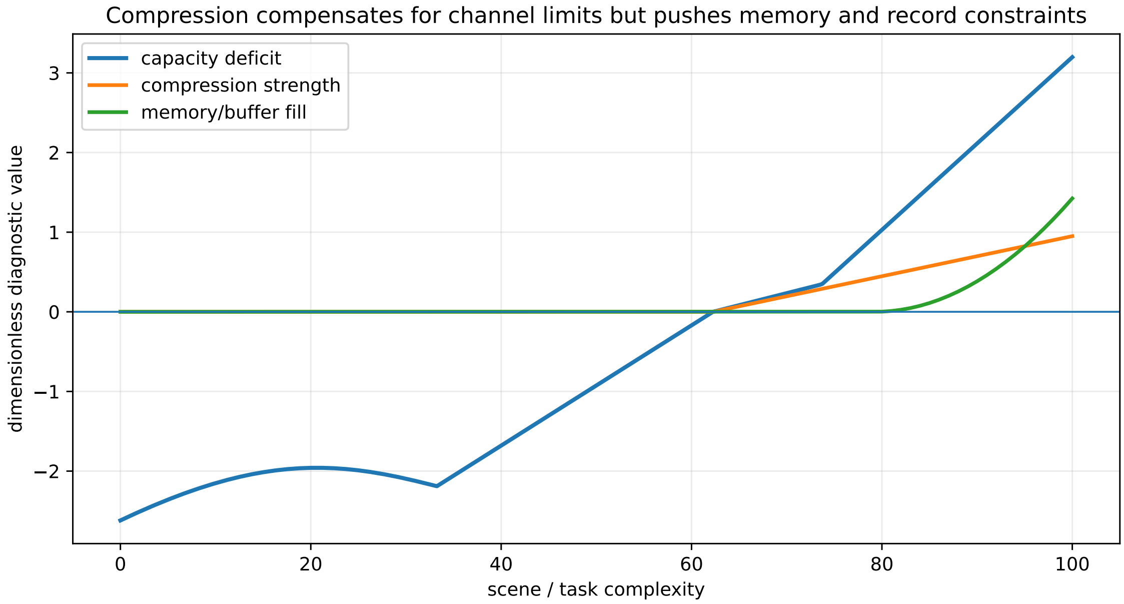

FIG. 2. Compression compensates for channel limits but pushes memory and record constraints. The same intervention that increases effective channel throughput increases buffer fill and capacity deficit.

Thus the record criterion is:

$$\begin{aligned}&\text{environmental correlation} + \text{accessible register}\\&\quad + \text{ record stability} \Rightarrow \text{operational outcome.}\end{aligned} \tag{26}$$

This is an interface claim. Stronger claims about wavefunction collapse, Born probabilities, Wigner's friend, or quantum Darwinism belong in a separate FDS-Q1 paper.

RELATION TO ACTIVE INFERENCE AND ROBOTICS

Active inference usually begins with an observation y_t and asks how an agent updates beliefs and acts to minimize variational free energy. FDS-O1 asks what physical conditions must hold for y_t to exist as a usable finite record. If the observation register is saturated, the agent receives

$$\tilde{y}_t = \pi_{\mathcal{O}}(y_t), \tag{27}$$

not y_t itself. The variational objective is then evaluated on compressed, delayed, merged, or lossy records:

$$F(q; \tilde{y}_t) \neq F(q; y_t). \tag{28}$$

This does not refute active inference. It supplies a measurement-capacity precondition for it.

For robotics and embodied AI, this distinction is practical. A robot does not fail only because its planner is wrong. It can fail because its camera, buffer, timestamping, memory, or record-stabilization pipeline has crossed capacity. O1 therefore functions as a diagnostic layer below inference and control.

DOMAIN-SPECIFIC PROJECTIONS

Physical instruments

In instrumentation, FDS-O1 predicts that increasing raw sampling can degrade usable records when it fills memory, triggers compression, or increases dead time. Bottleneck switching should appear as slope changes in error-latency curves. Fixed-memory overwriting should exhibit excess housekeeping heat relative to reversible or expanding-memory protocols.

Biological sensory systems

Biological observers are finite registers with active sampling, attention, memory, and metabolic constraints. FDS-O1 predicts that apparent perceptual objects are stabilized coarse partitions. When update capacity is insufficient, false merging, persistence, attentional blink, and delayed report can be interpreted as finite-register budget exits rather than mere subjective bias.

Robotics and AI systems

Robotic agents often fail upstream of planning. Camera frame buffers overflow; tracklets merge; asynchronous sensor streams desynchronize; memory garbage collection creates latency spikes; logs fill; and external storage changes access time. FDS-O1 provides a common vocabulary for these failures: they are finite-register budget

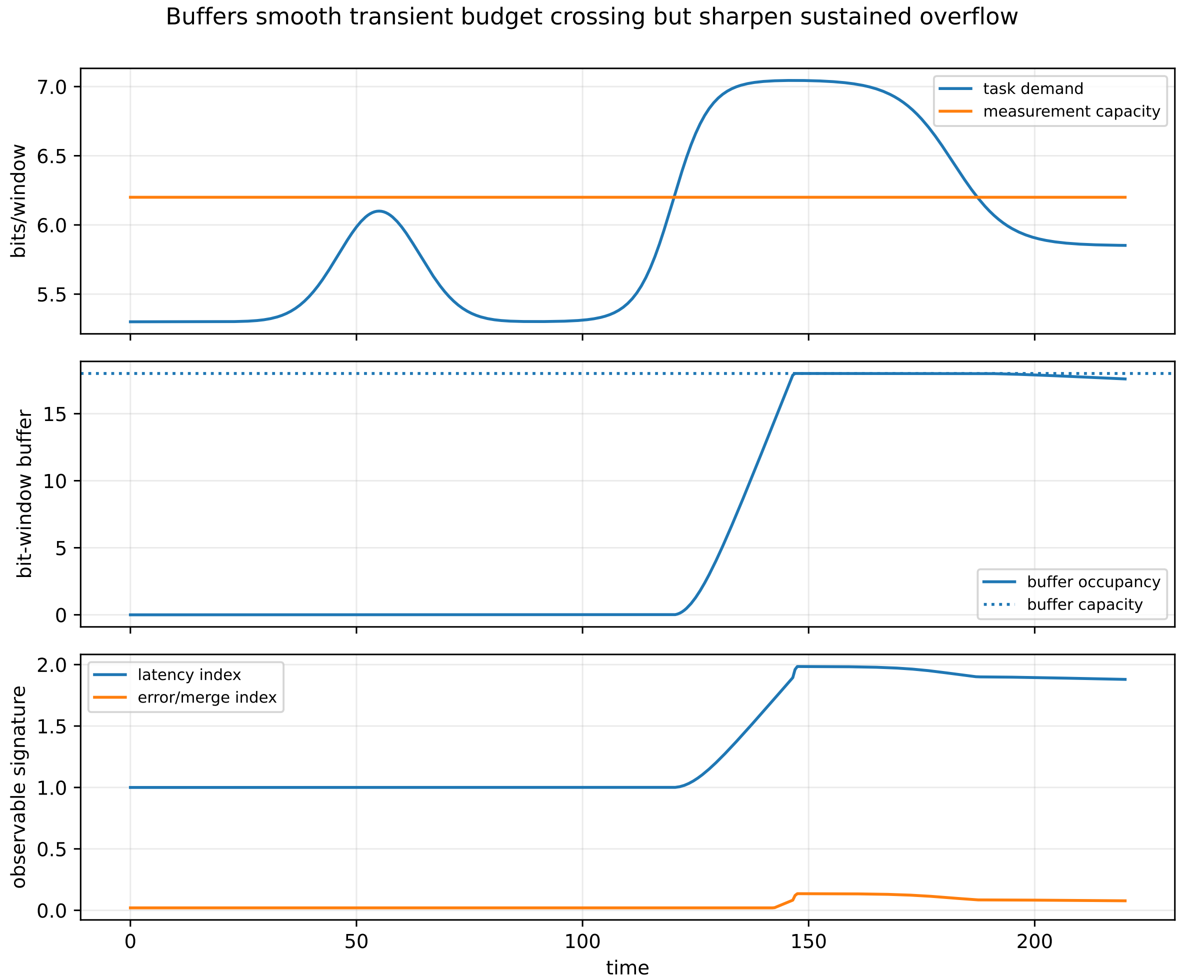

FIG. 3. Buffers smooth transient budget crossing but sharpen sustained overflow. The first overload pulse is mostly absorbed by buffer occupancy. The later sustained overload fills the buffer and generates latency and error/merge signatures.

crossings.

EXPERIMENTAL PROTOCOLS

Protocol 1 (Finite detector budget-crossing test)**.** *To test FDS-O1 in a detector or acquisition system:*

1. *Specify the observer-apparatus boundary and record carrier.*
2. *Estimate sensor, channel, memory, record-stability, buffer, externalization, and update capacities over the measurement window.*
3. *Define task family* Ψ *and target distortion* ε*.*
4. *Estimate* $R^{(\tau)}_{\min}(\varepsilon;\Psi)$ *using rate-distortion curves, calibration data, compression curves, Fisher information, or task-specific coding lower bounds.*
5. *Increase source complexity, noise, bandwidth demand, memory reuse pressure, or update rate until* $R^{(\tau)}_{\min}$ *crosses* C_{meas}*.*
6. *Measure error, latency, state merging, coarse-graining, reset frequency, externalization, buffer overflow, and heat output.*

Protocol 2 (Buffering test)**.** *Apply a short overload pulse and a sustained overload pulse with matched peak demand. FDS-O1 predicts that finite buffers absorb the short pulse primarily as latency, whereas sustained overload produces buffer overflow, state drops, false merging, externalization bursts, reset cascades, or hard failure.*

Protocol 3 (Reversible versus overwrite heat test)**.** *Compare two acquisition protocols with matched sensing and task demand: one using expanding memory with delayed erasure, and one using fixed memory with repeated overwrite. FDS-O1 predicts higher immediate housekeeping heat in the fixed-memory protocol, while*

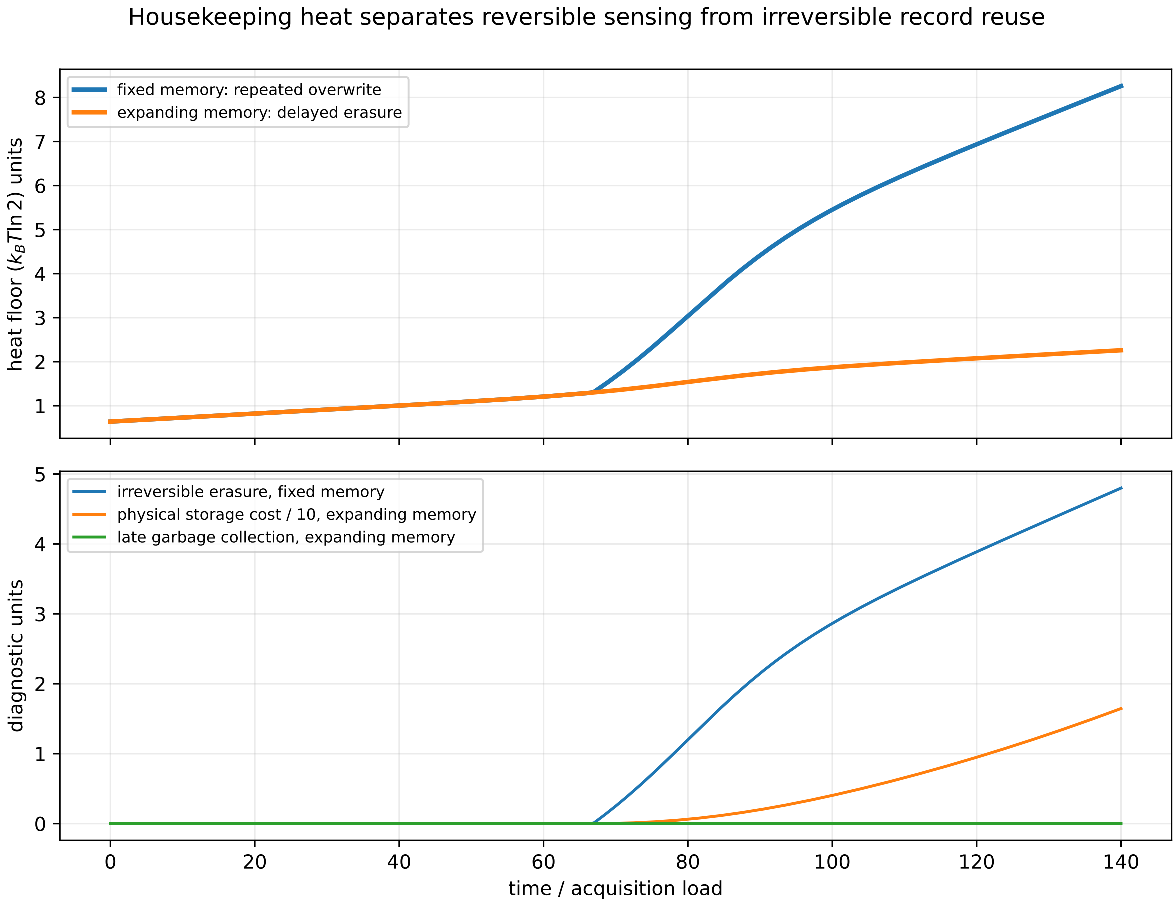

FIG. 4. Housekeeping heat separates reversible sensing from irreversible record reuse. Fixed-memory repeated overwrite produces a heat floor associated with erasure. Expanding memory postpones erasure but accumulates physical storage cost and may require later garbage collection.

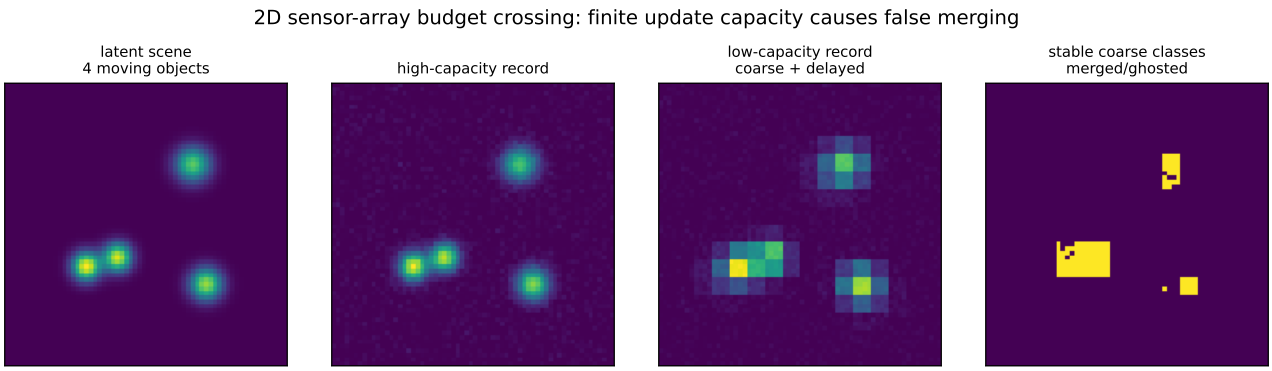

FIG. 5. Two-dimensional sensor-array budget crossing. A latent scene contains four moving objects. A high-capacity record preserves distinct objects. A low-capacity record with finite update budget, coarse resolution, and delayed refresh merges nearby objects and preserves ghost traces.

the expanding-memory protocol pays in storage and later garbage collection.

Protocol 4 (Sensor-array false-merging test)**.** *Use a camera or sensor array to track multiple moving objects while varying frame rate, buffer size, compression, and tracking memory. FDS-O1 predicts false merging, ghost persistence, delayed track updates, and track swapping once update demand exceeds accessible register capacity.*

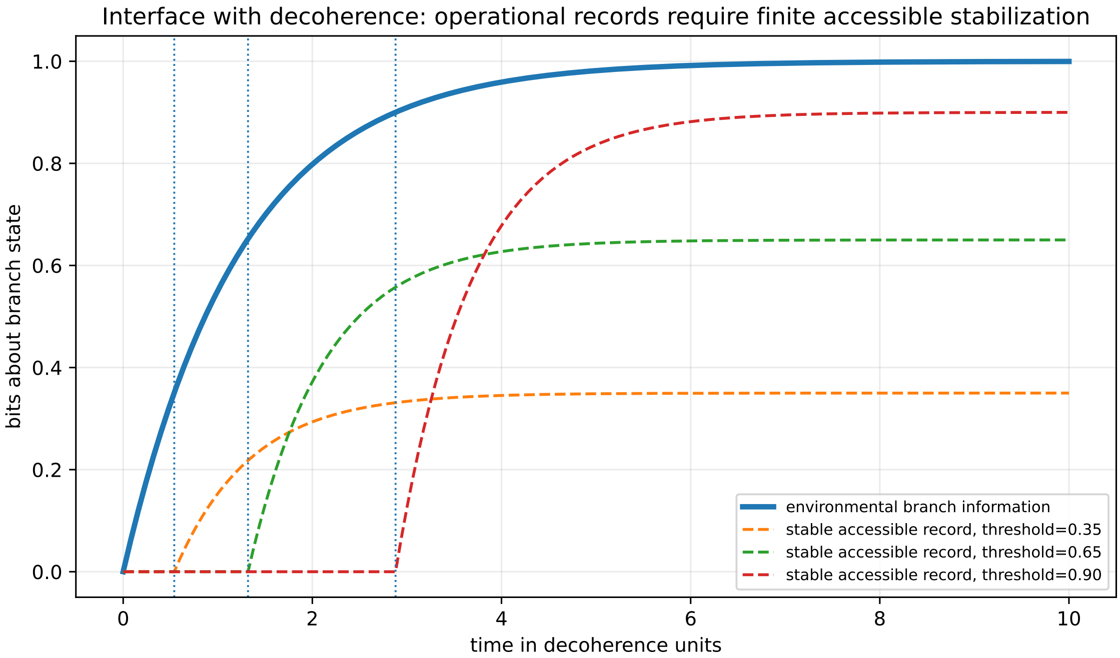

FIG. 6. Interface with decoherence. Environmental information about a branch can grow continuously, but finite observers obtain operational records only when accessible stabilization crosses task thresholds. This is a record criterion, not a replacement for decoherence theory.

TABLE II. Relationship between active inference concepts and FDS-O1 measurement-capacity variables.

Active inference concept	**FDS-O1 counterpart**	**Finite-capacity implication**
Observation y_t	Stabilized finite record z_t	Observation exists only after record formation
Generative model	Projection $\pi_{\mathcal{O}}$ plus update policy	Model operates on available distinctions
Precision weighting	Allocation of distinguishability capacity	Precision can be limited by sensor, memory, or update bottlenecks
Sensory attenuation	Controlled reduction of measurement demand	Agent may lower demand to avoid crossing
Epistemic action	Action to increase future C_{meas} or reduce $R_{\text{min}}^{(\tau)}$	Looking, moving, probing, or sampling changes the capacity ledger
Free-energy minimization	Inference after finite record formation	Saturated registers distort the inference input
Model failure	Budget crossing, delayed records, state merging	Some failures are measurement-capacity failures, not inference failures

LIMITATIONS AND FALSIFICATION

First, the paper is a finite-record measurement model, not a derivation of the fundamental laws. Second, C_{meas} is a schematic capacity ledger; real detectors require detailed modeling of noise, calibration, back-action, control loops, dead time, hysteresis, quantum efficiency, environmental coupling, and hardware scheduling. Third, Landauer accounting applies only to physically implemented logically irreversible operations under the relevant thermodynamic assumptions. Fourth, not every interaction is a measurement. Record stability and accessibility matter. Fifth, observer-dependence here is operational, not arbitrary subjectivism.

The strong version of FDS-O1 would be undermined by any of the following:

1. a complete physical account of operational measurement requiring no finite record carrier, no stable trace, no boundary, no readout channel, and no capacity constraint;

2. a detector that reliably stabilizes unlimited distinctions under bounded resources and fixed error tol-

erance;

3. persistent full-fidelity measurement when $R^{(\tau)}_{\min}(\varepsilon;\Psi)$ exceeds all sensor, channel, memory, record-stability, buffer, externalization, and update capacities;

4. repeated finite-memory irreversible record reuse below generalized Landauer accounting after all reservoirs, feedback records, correlations, and work sources are included;

5. no observable change in error, latency, coarse-graining, externalization, reset, heat, buffering, or failure under controlled budget crossing;

6. active inference or control performance that remains invariant under severe manipulation of record availability, delay, compression, and merging, after task difficulty is otherwise held fixed.

CONCLUSION

An observer is not a magical epistemic primitive. It is a finite physical register that draws distinctions, stabilizes records, updates them, buffers them, and sometimes erases them under limited resources. Measurement is not just coupling; it is record formation that survives long enough to be used. Once this is made explicit, measurement inherits the same finite-budget structure developed in FDS-T1: accessible capacity is bottlenecked, task demand can exceed capacity, and budget crossing forces observable exits.

The v0.2 development strengthens O1 by replacing independent bottlenecks with dynamically coupled capacities, adding finite buffers, separating reversible sensing from irreversible housekeeping heat, adding a sensor-array simulation, and clarifying the relation to decoherence and active inference. The resulting framework is not a replacement for detector physics, quantum foundations, or robotics theory. It is a measurement-capacity diagnostic: if the finite register cannot form the record, then later inference, control, reporting, or theory-building starts from a compressed, delayed, merged, or missing observation.

FDS-O1 therefore supplies the operational trident's first anchor. T1 states the finite-observer budget. O1 turns that budget into a measurement model. O2 should treat time as ordered irreversible update. O3 should treat the Second Law as the macroscopic cost of finite record maintenance. The immediate empirical signature is simple: when measurement demand crosses accessible capacity, finite observers do not continue measuring at full fidelity. They merge states, buffer and delay records, externalize, reset memory, dissipate housekeeping heat, relax the task, or fail.

Notation Summary

Simulation Parameters

The simulations are deterministic and use fixed synthetic parameter values in `code/generate_results.py`. The dynamic-bottleneck simulation uses a scene complexity axis $u \in [0, 100]$, rising task demand, a compression policy activated by channel stress, memory fill dynamics, and record-stability penalties from compression. The buffering simulation uses a short overload pulse and a sustained overload pulse with finite buffer capacity. The heat simulation compares fixed-memory overwriting with expanding-memory delayed erasure. The sensor-array simulation uses 64×64 images with moving Gaussian objects and coarse block-averaged low-capacity observation. The decoherence-interface simulation uses a saturating environmental information curve and several finite record thresholds. No proprietary data, detector data, quantum experimental data, or human-subject data are used.

Reproducibility Checklist

1. Code availability: all simulation code is included in the replication package.
2. Deterministic execution: the random seed is fixed for synthetic image noise.
3. Figure reproduction: running `python code/generate_results.py` regenerates all figures and CSV outputs.
4. Data status: all numerical outputs are synthetic demonstrations generated from the stated model.
5. Platform independence: the code uses standard Python scientific libraries.

Boundary of Applicability

FDS-O1 applies to systems that function as finite physical registers: they have record carriers, finite readout, finite stability, finite update, buffers, and finite task windows. It does not apply to idealized mathematical observers with unbounded access, nor does it make claims about fundamental collapse or nonunitary quantum dynamics. It is compatible with unitary microscopic evolution and with standard detector-specific modeling.

CODE AVAILABILITY

The simulation code used to generate Figs. 1–6 is included in the accompanying replication package

TABLE III. FDS-O1 notation summary.

Symbol	**Meaning**
$\mathcal{O}$	finite observer or distinction-register
$\mathcal{D}$	detector or measurement apparatus
Ω	physical possibility space
$\pi_{\mathcal{O}}$	finite distinction projection implemented by $\mathcal{O}$
$\mathcal{Z}_{\mathcal{O}}$	accessible record classes
$N_{\mathcal{O}}$	number of operationally distinguishable record classes
$C_{\mathcal{O}}$	bit capacity $\log_2 N_{\mathcal{O}}$
C_{sens}	usable sensor-resolution capacity
C_{chan}	readout/channel capacity
C_{mem}	internal memory capacity
C_{rec}	stable record capacity over retention window
$C_{\text{ext}}^{\text{eff}}$	effective externalized record capacity after overhead
$I_{\text{update}}^{\max}$	maximum irreversible update throughput
C_{meas}	accessible measurement capacity
$R_{\min}^{(\tau)}(\varepsilon;\Psi)$	minimal task-relevant distinction demand
Δ_{O1}	measurement capacity deficit
B_{buf}	finite buffer occupancy
P_{hk}	housekeeping power associated with irreversible record reuse
τ_{rec}	finite accessible record-formation time

under `code/generate_results.py`. Running the script regenerates all figures (PDF and PNG) and CSV tables in a single pass. The public repository path is https://github.com/yiningwu-research/Distinction-Theory/tree/main/models/fds_o1. Related DT/FDS archival materials, including the Formal Core (FDS-0), the general archive, and the claim registry, are maintained in the same public repository.

AI ASSISTANCE DISCLOSURE

AI-assisted tools were used for language polishing, structural feedback, LaTeX drafting support, and code-debugging assistance. The author reviewed and edited all content and remains responsible for all claims, references, simulations, and conclusions. No AI system is listed as an author.

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