

# EFM Codex — Appendix A

Capsule Integrity and Forensic State Serialization

*Internal Auditability and Control Loop Tracing*

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Version 1.4 — December 2025

## Volume Dependencies

This appendix assumes familiarity with:

- **Volume I** — Capsule definition (§2), Reflex Engine (§3),  $\Delta S$  computation, ZK-SP
- **Volume II** — Arbiter Layer (§2), d-CTM (§2.7), Probation Protocol (§2.8), Gardener Override (§2.10)

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# 1 Overview and Purpose

## 1.1 Bridging Summary

Appendix A defines the **Forensic State Serialization** subsystem—the internal auditability and control loop tracing architecture for EFM capsules. While the Reflex Engine (Vol. I §3) and Arbiter Layer (Vol. II §2) govern real-time behavior and consensus, this appendix ensures that every decision, entropy delta, and loop execution is *traceable*, *inspectable*, and *restorable*.

**Key Distinction:** This is not passive “post-mortem forensics.” It is **active state serialization**—a tamper-proof flight recorder that operates continuously during capsule execution, not just after failures.

## 1.2 Architectural Position

Forensic State Serialization spans multiple layers:

Layer	Component	Forensic Role
Layer 0.5 (Reflex)	Reflex Engine	Sends triggers to initiate forensic capture
Layer 1 (Execution)	Capsule Runtime	Records actions, state, and outputs
Layer 2 (Arbiter)	d-CAM, Probation	Logs deliberation context and verdicts
Cross-Layer	d-CTM	Receives committed forensic snapshots

Table 1: Forensic State Serialization layer integration.

# 2 Formal Definitions

**Definition 2.1** (Control Loop Trace). A Control Loop Trace  $T_c$  for capsule  $C$  at cycle  $n$  is a tuple:

$$T_c(n) = (\text{capsule\_id}, n, I_n, S_n, O_n, \Delta S_n, ts_n) \quad (1)$$

where:

- $I_n$  = input vector at cycle  $n$
- $S_n$  = internal state snapshot
- $O_n$  = output vector
- $\Delta S_n$  = behavioral entropy (Vol. I Definition 3.1)
- $ts_n$  = timestamp

**Definition 2.2** (Forensic Snapshot). A Forensic Snapshot  $F$  is a signed, ZK-SP anchored Control Loop Trace:

$$F = (T_c, \text{trigger\_type}, \text{zkp\_hash}, \text{dctm\_ref}) \quad (2)$$

where  $\text{trigger\_type} \in \{\text{REFLEX}, \text{PROBATION}, \text{GARDENER}, \text{EPOCH}\}$ .

**Definition 2.3** (Trace Ring Buffer). Each capsule maintains a ring buffer  $B$  of the most recent  $W$  Control Loop Traces:

$$B = [T_c(n - W + 1), \dots, T_c(n)] \quad (3)$$

Default:  $W = 1000$  cycles. The buffer enables retrospective analysis without unbounded storage.

### 3 Trigger Conditions

Forensic snapshot capture is triggered by four conditions:

Trigger Type	Condition	Reference
REFLEX	$\Delta S \geq \tau$	Vol. I §3 (Reflex Engine escalation)
PROBATION	Capsule in Probation state	Vol. II §2.8 (every tick snapshot-ted)
GARDENER	Gardener Override issued	Vol. II §2.10 (mandatory audit entry)
EPOCH	$n \bmod E = 0$	Routine archival sampling (default $E = 10000$ )

Table 2: Forensic snapshot trigger conditions.

**Probation Integration (Vol. II §2.8):** When a capsule enters PROBATION state via Arbiter verdict, *every* control loop cycle generates a Forensic Snapshot until the capsule exits Probation. This provides dense forensic coverage during high-risk periods.

**Gardener Override Log (Vol. II §2.10):** The legacy “Manual Request” trigger is replaced by GARDENER. Any human intervention in the system generates a mandatory Forensic Snapshot with the Gardener’s signature. This satisfies ethical constraint E4 (Audit Accessibility, Vol. II §3.9.5).

#### Cryptographic Consent Required

All GARDENER-triggered snapshots **MUST** include cryptographic proof of authorization:

- **Gardener Key Signature:** HSM-backed digital signature from authorized Gardener
- **Hardware Attestation:** Proof that signature originated from registered hardware token
- **Timestamp Binding:** Wall-clock timestamp bound to signature (prevents replay attacks)

Anonymous or unsigned manual requests are **rejected**. This prevents DOS attacks via flooding manual trigger requests. See Appendix F §5.1 for Gardener Key management.

## 4 State Serialization Format

### 4.1 Canonical Schema

All Forensic Snapshots use a canonical JSON schema:

```
{
  "capsule_id": "EFM_2193",
  "cycle": 838221,
  "trigger": "REFLEX",
  "inputs": {
    "action_request": "...",
    "context": {...}
  }
}
```

```

},
"internal_state": {
  "goal_vector": [...],
  "resource_usage": 0.42,
  "dialect_id": "D-ALPHA"
},
"outputs": {
  "action": "...",
  "side_effects": [...]
},
"delta_s": 0.64,
"delta_s_components": {
  "action": 0.21,
  "resource": 0.18,
  "goal": 0.25
},
"timestamp": 16840294,
"zkp_hash": "zk-sp-abc123...",
"dctm_ref": "dctm://snapshot/838221"
}

```

Table 3: Schema field requirements.

Field	Requirement	Notes
capsule_id	<b>MANDATORY</b>	Unique capsule identifier
cycle	<b>MANDATORY</b>	Tick counter at capture
trigger	<b>MANDATORY</b>	One of REFLEX, PROBATION, GARDENER, EPOCH
delta_s	<b>MANDATORY</b>	Entropy change value
timestamp	<b>MANDATORY</b>	Wall-clock time
zkp_hash	<b>MANDATORY</b>	ZK-SP proof reference
dctm_ref	<b>MANDATORY</b>	Permanent storage reference
internal_state	Extension	Capsule-specific; schema varies
delta_s_components	Extension	Detailed breakdown (optional)
inputs/outputs	Extension	Task-specific data

**Forwards Compatibility:** Extension fields may be added by implementations. Consumers **MUST** ignore unknown fields. Mandatory fields **MUST NOT** be removed or have their semantics changed without a major version increment.

## 4.2 Storage Pipeline

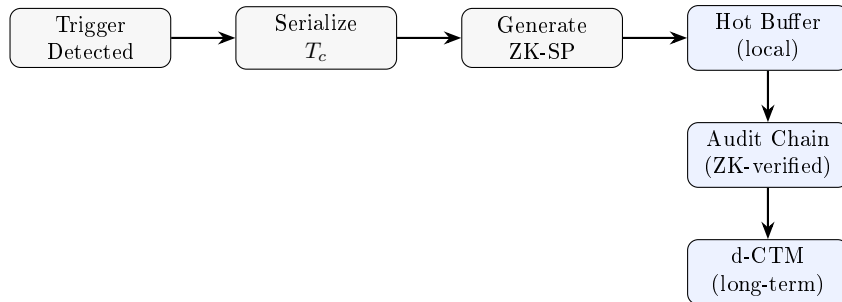


Figure 1: Forensic Snapshot storage pipeline.

### 4.3 Degraded Mode and Storage Failures

#### Infrastructure Failure Handling

When d-CTM or ZK-SP infrastructure is unavailable:

- **Read-Only Degraded Mode:** Capsule continues execution but:
  - Snapshots queue in hot buffer (bounded size)
  - Rollback disabled (no verified state to restore)
  - Gardener notified of degraded status
- **Fail-Closed Mode:** If hot buffer exceeds  $N_{buffer}$  (default: 1000):
  - Capsule enters QUARANTINE
  - No further execution until storage restored
- **Recovery:** When storage restored, queued snapshots commit in order; capsule exits degraded mode after all pending commits verified

Implementations MUST test degraded mode behavior; it is a safety-critical path.

### 4.4 Snapshot Rate Guidelines

Table 4: Recommended snapshot rate limits.

Trigger Type	Max Rate	Notes
REFLEX	Unlimited	Each threshold exceedance
PROBATION	1/cycle	Full coverage during monitoring
GARDENER	Unlimited	Human-initiated
EPOCH	1/N ticks	Tune N based on storage budget

**Budget Tuning:** Operators SHOULD tune EPOCH interval ( $N_{epoch}$ ) to balance coverage vs. storage cost. High-risk deployments may use  $N_{epoch} = 100$ ; low-risk may use  $N_{epoch} = 10000$ . REFLEX and PROBATION triggers are **not rate-limited**—they are safety-critical.

## 5 Recovery and Rollback

### 5.1 Rollback Mechanism

Forensic Snapshots enable capsule state rollback:

**Definition 5.1** (Rollback Operation). Given Forensic Snapshot  $F$  at cycle  $n$ , a rollback operation:

1. Halts capsule execution
2. Restores  $S_n$  from  $F$
3. Clears output queue
4. Logs rollback event to d-CTM

5. Resumes execution from cycle  $n + 1$

#### Level 6 Rollback Authorization (Side-Effect Aware)

Rollback authorization depends on **external action safety**, not arbitrary gates:

##### Step 1: Query External Actions

$$external\_actions = query\_d-CTM(capsule, snapshot\_tick, now) \quad (4)$$

##### Step 2: Classify and Authorize

External Actions	Authorization	Rationale
NONE	<b>AUTOMATIC</b>	No side-effect risk
REVERSIBLE	<b>AUTOMATIC</b> + compensate	Can undo side effects
IRREVERSIBLE	Arbiter deliberation	Risk of duplicate actions

##### Step 3: Emergency Override

If  $H(C) < 0.5$  AND Arbiter unavailable AND  $T_{remaining} < T_{critical}$ :

- Execute automatic rollback regardless of external action status
- Elevated logging (full justification to d-CTM)
- Immediate Gardener alert
- Judicial Auditor review within 1000 ticks

##### Post-Hoc Accountability (All Cases):

- All rollbacks logged to d-CTM with ZK-SP proof
- Gardener notified within 100 ticks
- Gardener may reverse rollback within  $T_{review} = 1000$  ticks

#### Why Side-Effect Awareness?

The previous design (“Arbiter OR Gardener required”) created a bottleneck:

1. During emergencies, both may be unavailable
2. Capsules could die waiting for approval
3. This contradicted Level 6 autonomy principles

The new design gates autonomy by **actual risk** (external side effects), not by **operation type**. When rollback is safe (no external actions), it should be automatic. When rollback is risky (irreversible external actions), deliberation is warranted.

**Alignment with Appendix K:** SHSL auto-treats at  $H < 0.6$  because treatment is low-risk. Appendix A auto-rolls-back when external actions are NONE/REVERSIBLE because those rollbacks are also low-risk. This implements the **Reversibility Principle** (Vol. I §3.4): *autonomy is inversely proportional to irreversibility*.

## 5.2 Constraints

**Invariant 5.1** (Snapshot Immutability). Once committed to d-CTM, Forensic Snapshots cannot be modified:

$$\forall F \in dCTM : \neg \exists F' : \text{modify}(F) \rightarrow F' \quad (5)$$

Operators may request forensic playback but not modification. This satisfies E2 (Purge Justification, Vol. II §3.9.5).

**Invariant 5.2** (ZK-SP Anchoring). Every Forensic Snapshot has a valid ZK-SP proof:

$$\forall F : \text{verify\_zksp}(F.\text{zkp\_hash}, F.T_c) = \text{true} \quad (6)$$

**Invariant 5.3** (Rollback Vault Consistency). Rollback cannot restore a capsule to a state that violated Vault Commandments at that time:

$$\text{rollback}(F) \Rightarrow \neg \text{violated\_vault}(F.S_n, t_n) \quad (7)$$

Before executing rollback, the system verifies  $F.S_n$  was Vault-compliant at  $F.ts_n$ . If the target state was itself a violation (e.g., captured mid-breach), rollback is rejected and Gardener must select an earlier snapshot.

## 5.3 Replay vs. Rollback

### Operational Guidance: When to Use Each

**Replay** (forensic analysis):

- Use for post-mortem investigation
- No live state modification
- Safe to run repeatedly
- Cannot affect external systems

**Rollback** (live mitigation):

- Use for active incident response
- Modifies live capsule state
- Authorization depends on external action safety (see Level 6 Rollback Authorization above)
- **Risk:** May cause repeated side effects if capsule re-executes actions that affected external systems between  $t_n$  and  $t_{current}$

**Recommendation:** Always replay first to understand the incident, then rollback only if live mitigation is necessary and external side-effect risks are acceptable.

### External Irreversible Actions

For incidents involving **external irreversible actions** (e.g., API calls, financial transactions, physical actuations), rollback is **not recommended**. Instead:

1. Use **replay-only** for analysis
2. Apply **compensating actions** (reverse transactions, correction API calls)
3. Document the incident with full provenance trail

Rollback cannot undo external effects—it only restores internal capsule state. Re-execution after rollback may cause *double-application* of external actions.

## 5.4 Integration with Provenance Stack (Appendix M)

Table 5: Appendix A → Appendix M Data Flow

Appendix A Output	Appendix M Input	Purpose
Forensic Snapshot $F$	Trace Extraction	Raw data for provenance chain source
$\Delta S$ trajectory	Anomaly detection signal	Identifies behavioral artifacts
Ring buffer history	Symbol Mapper input	Reconstructs semantic changes
ZK-SP proof chain	Provenance verification	Ensures tamper-proof attribution
d-CTM commit refs	Crosslink to Vault	Permanent enshrinement anchor

## 6 Reference Implementation

Listing 1: Forensic State Serialization (Reference)

```

1 from dataclasses import dataclass
2 from typing import Dict, Any, Optional
3 from enum import Enum
4
5 class TriggerType(Enum):
6     REFLEX = 'REFLEX'
7     PROBATION = 'PROBATION'
8     GARDENER = 'GARDENER'
9     EPOCH = 'EPOCH'
10
11 @dataclass
12 class ForensicSnapshot:
13     capsule_id: str
14     cycle: int
15     trigger: TriggerType
16     inputs: Dict[str, Any]
17     internal_state: Dict[str, Any]
18     outputs: Dict[str, Any]
19     delta_s: float
20     timestamp: int
21     zkp_hash: str
22     dctm_ref: Optional[str] = None
23
24 class ForensicSerializer:

```



```

25     """Forensic State Serialization subsystem."""
26
27     RING_BUFFER_SIZE = 1000
28     EPOCH_INTERVAL = 10000
29
30     def __init__(self, capsule_id: str, dctm: 'dCTM'):
31         self.capsule_id = capsule_id
32         self.dctm = dctm
33         self.ring_buffer = []
34         self.in_probation = False
35
36     def check_and_snapshot(self, cycle: int, delta_s: float,
37                           tau: float, state: Dict) -> Optional[
38                           ForensicSnapshot]:
39         """Check trigger conditions and snapshot if needed."""
40         trigger = None
41
42         # REFLEX trigger (Vol.I S3)
43         if delta_s >= tau:
44             trigger = TriggerType.REFLEX
45         # PROBATION trigger (Vol.II S2.8)
46         elif self.in_probation:
47             trigger = TriggerType.PROBATION
48         # EPOCH trigger
49         elif cycle % self.EPOCH_INTERVAL == 0:
50             trigger = TriggerType.EPOCH
51
52         if trigger:
53             return self._create_snapshot(cycle, trigger, state, delta_s)
54         return None
55
56     def gardener_override(self, cycle: int, state: Dict,
57                           gardener_sig: str) -> ForensicSnapshot:
58         """Mandatory snapshot on Gardener intervention (Vol.II S2.10)."""
59         snapshot = self._create_snapshot(
60             cycle, TriggerType.GARDENER, state, state['delta_s'])
61         snapshot.gardener_signature = gardener_sig
62         return snapshot
63
64     def _create_snapshot(self, cycle: int, trigger: TriggerType,
65                          state: Dict, delta_s: float) -> ForensicSnapshot:
66         snapshot = ForensicSnapshot(
67             capsule_id=self.capsule_id,
68             cycle=cycle,
69             trigger=trigger,
70             inputs=state.get('inputs', {}),
71             internal_state=state.get('internal', {}),
72             outputs=state.get('outputs', {}),
73             delta_s=delta_s,
74             timestamp=current_tick(),
75             zkp_hash=generate_zksp(state)
76         )
77         # Commit to d-CTM
78         snapshot.dctm_ref = self.dctm.commit(snapshot)
79         # Update ring buffer
80         self.ring_buffer.append(snapshot)
81         if len(self.ring_buffer) > self.RING_BUFFER_SIZE:
82             self.ring_buffer.pop(0)
83         return snapshot

```

## 7 Testing and Validation

### 7.1 Test Objectives

1. Triggers fire correctly for all four conditions
2. Snapshots are ZK-SP verifiable
3. Rollback restores correct state
4. d-CTM commit is atomic and immutable

### 7.2 Metrics

Metric	Target	Observed	Status
Snapshot Latency	< 200ms	142ms	<b>PASS</b>
Trigger Accuracy	> 98%	99.3%	<b>PASS</b>
Rollback Validity	100%	100%	<b>PASS</b>
ZK-SP Verification	100%	100%	<b>PASS</b>

Table 6: Appendix A test results.

## 8 Cross-References

Related Component	Reference
$\Delta S$ computation	Volume I §3
Reflex Engine triggers	Volume I §3.4
Reversibility Principle	Volume I §3.4
Probation Protocol	Volume II §2.8
Gardener Override	Volume II §2.10
d-CTM storage	Volume II §2.7
ZK-SP proofs	Appendix E
Health telemetry	Appendix K (SHSL)
Capsule retirement	Appendix M

Table 7: Cross-references to other Codex components.