

# Document 4: CSTP – Graph Lifecycle

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## 1. Abstract

The Graph Lifecycle Model extends Cryptographic State Transition Proofs (CSTP) from linear, single-asset timelines to multi-asset, branching, merging, and interdependent state graphs. Each asset is represented as a node, and each transition is represented as a cryptographically bound edge. The system ensures that at any point in time, an auditor can prove not only that a given transition occurred, but also that it was consistent with all related assets, constraints, and prior states within the graph — without accessing any of the underlying data.

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## 2. Technical Field

This work operates within:

- Distributed cryptographic state management
  - Directed acyclic graphs (DAGs) for provenance and lifecycle
  - Multi-asset and multi-epoch state validation
  - Irreversible cryptographic auditability and dependency tracking
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## 3. Background

Linear state models (Document 2) solve single-asset state transition proofs. However, real systems require:

- **Assets that branch** (forking a dataset into derivatives)
- **Assets that merge** (combining multiple records or keys)
- **Assets that depend on others** (compliance chains, root-of-trust structures)
- **Cross-asset destruction or expiry**
- **Simultaneous transitions across multiple nodes**

Existing Merkle-based systems track independent logs or chains, but do not encode interdependencies. This document defines a general model: **Merkle-anchored transition DAGs**.

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## 4. Definitions

Term / Symbol	Meaning
Node ( $N_i$ )	Represents an asset or sub-asset in the system
Edge ( $E_{ij}$ )	A transition from node $i$ to node $j$
Transition-State (TS)	Cryptographic record of an edge (reuse from Document 2)
DAG	Directed Acyclic Graph of transitions; cycles are disallowed
Parent Set $P(N_i)$	All nodes whose outputs feed into $N_i$
Child Set $C(N_i)$	All nodes derived from $N_i$
Asset Graph (G)	Set of all N and E defining an ecosystem of states
Merge Transition	Multiple TS inputs → one output
Fork Transition	One TS input → multiple outputs

## 5. System Overview

Core Components (extends Document 3 CSTP Core):

- **Graph Controller** – Maintains valid DAG of nodes and transitions
- **Dependency Validator** – Ensures no cycles or invalid parent references
- **Graph Merkle Accumulator** – Commits all edges (transitions) into per-epoch Merkle trees
- **Root Chain** – Chained hash of epoch roots (same as Document 2 & 3)
- **Graph Receipt Store** – Stores each transition-state receipt along with parent references
- **Verifier** – Independently reconstructs graph branches to confirm transitions

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## 6. Core Mechanism

### 6.1 Graph Construction

- Each transition (creation, migration, merge, destruction) becomes an **edge  $E_i$**
- Each asset or sub-asset becomes a **node  $N_i$**
- Edges always move forward; no backward cycles permitted
- Each edge includes:
  - `asset_id` or multiple IDs (merge case)
  - `parent_commitment(s)`
  - `commitment_current`

- epoch, transition\_type

## 6.2 Merge and Fork Logic

Transition Type	Definition
Fork	$N_i \rightarrow \{N_j, N_k\}$ . E.g. dataset duplicated or branched
Merge	$\{N_a, N_\beta\} \rightarrow N_\gamma$ . E.g. key shares recombined, datasets joined
Multi-Destroy	$\{N_a, N_\beta\} \rightarrow \text{NULL digest states}$
Migration	$N_i (\text{RSA}) \rightarrow N_i (\text{PQ crypto})$

Each transition emits a **transition-state receipt** including all parent references.

## 6.3 Transition-State Commitment (Graph-Aware)

```
C_graph = H(
    sorted(asset_ids) ||
    sorted(parent_commitments) ||
    epoch ||
    transition_type ||
    salt
)
```

## 6.4 Merkle and Chain Anchoring

- All C\_graph values for epoch e → Merkle root  $R_e$
  - Root chain persists:  $\text{chain}_e = H(\text{chain}_{e-1} \parallel R_e)$
  - Verifiable without asset data, only receipts + commitments
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## 7. Receipt Structure (Graph Version)

Field	Description
asset_ids	One or more identifiers involved in transition
parent_commitments	Commitments of all input states
commitment	New transition commitment
merkle_path	Proof of inclusion in epoch Merkle tree
epoch_root	Merkle root of that epoch
chain_root	Cumulative chain of roots
state_before	Optional hash of combined inputs
state_after	Hash of output or NULL_DIGEST for destruction

## 8. Verification

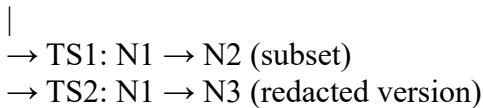
To verify a transition:

1. Check no cycles exist in parent chain
2. Recompute C\_graph from asset\_ids + parent\_commitments
3. Reconstruct Merkle path → confirm matches epoch\_root
4. Confirm epoch\_root belongs in root chain
5. Optionally verify state\_before/state\_after matches expectations (if provided)
6. Accept transition only if chain continuity is intact

## 9. Example Graph Scenarios

### 9.1 Fork Example

Dataset A (N1)



### 9.2 Merge Example

Key Share K1 + Key Share K2 → Recombined Key (N4)

### 9.3 Destruction Cascade

N1, N2, N3 → TS(destroy\_all) → NULL Digest states

## 10. Advantages

- ✓ Models real-world multi-asset dependencies
- ✓ Enables proving correct merge/split/migration without accessing data
- ✓ Works offline — only commitments and receipts needed
- ✓ Compatible with Documents 1–3 (EIVs, Transition-States, CSTP Core)
- ✓ Deterministic, acyclic, verifiable structure

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**End of Document 4 – CSTP Graph Lifecycle**