PRECOP: Predictive Covenant Oracle Protocol

Sovereign Conditional State Machines and Work-Weighted Oracle Resolution on Bitcoin L1

laz1m0v

March 2026 \ Version 0.0.2

Abstract

Decentralized finance on the Bitcoin base layer has come to rely predominantly on federated oracle committees and secondary consensus layers, reintroducing the trust asymmetries that Bitcoin was designed to eliminate. This paper introduces PRECOP (Predictive Covenant Oracle Protocol), a formally specified protocol for trust-minimized sovereign DeFi on Bitcoin Layer 1, requiring no softforks.

The core contribution is the **Template-Enforced UTXO State Machine (TUSM)** — a covenant-enforced automaton anchored to the UTXO set via Taproot key commitments, executed by the Simplicity Bit Machine through a 5-leaf MAST topology. PRECOP implements collateralized debt positions (CDPs), constant-product AMMs, and multi-standard asset exchange (BRC-20, Runes, Ordinals) entirely on L1. A layered oracle architecture transitions from Schnorr attestation (Bootstrap Phase) to Binohash Proof-of-Work (Thermodynamic Phase), progressively replacing identity-based trust with verifiable energy expenditure. Precopscan, a stateless forensic observer, reconstructs the complete protocol state from Bitcoin L1 alone using seven cryptographically committed probe addresses. Formal proof sketches are provided for state transition determinism, oracle anti-replay, and 128-bit arithmetic integrity.

Contents

"Sovereign conditional state management where the covenant is the consensus."

1 1. Introduction

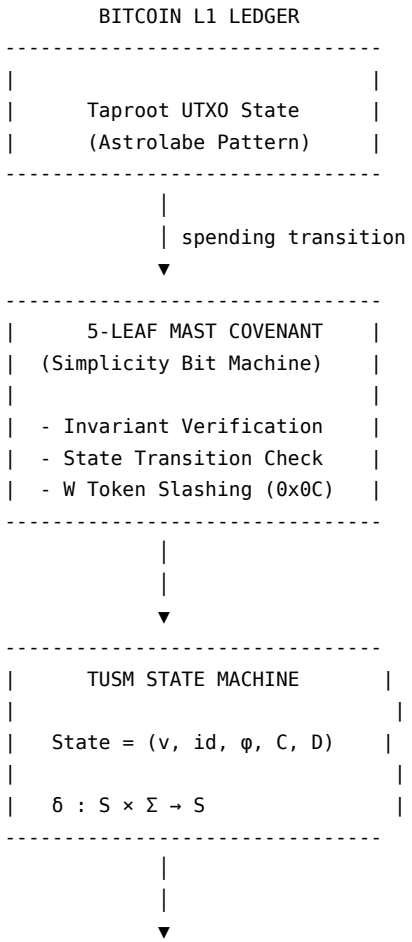
1.1 1.1 The Predictive Oracle Paradox

Exogenous state resolution within a deterministic execution environment represents the primary bottleneck for decentralized finance on Bitcoin. Historically, dominant architectures have mitigated this deficiency by introducing trusted federations (multisig quorums) or secondary consensus layers (Proof-of-Stake sidechains). These models reintroduce vulnerabilities to Byzantine faults and establish an asymmetry of trust that contradicts the fundamental axiom of Bitcoin: rely on cryptographic proof, not trust.

We propose a solution to the oracle paradox using a proof-of-work mechanism. PRECOP resolves exogenous states via **Work-Weighted Oracle Resolution**. In this model, resolution is no longer a declarative act by a trusted committee; it is a cryptographic proof bound to tangible energy expenditure. This transforms the oracle from a private signer into a **cryptographically sealed variable** within an expressive covenant-enforced state machine.

1.2 1.2 Protocol Architecture

The system operates as a rigidly defined automaton. The state machine is anchored to the Unspent Transaction Output (UTXO) set, where state transitions are authenticated by user signatures and mathematically enforced by the covenant.



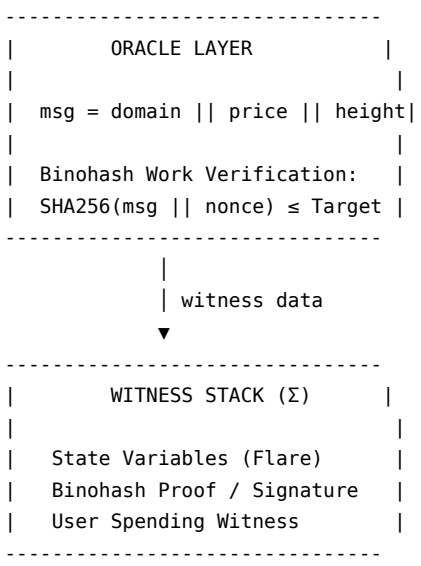


Figure 1: Template-Enforced UTXO State Machine (TUSM) Architecture

1.3 1.3 Strictly Isolated Architecture and Topology

Fork Transparency. PRECOP builds directly on two upstream open-source projects with specific modifications. The Simplicity covenant layer uses the `simplicity-unchained` runtime from Blockstream Research [6], extended with: (1) **Dynamic Indexing** — a single `asset_protocol` byte in the witness stack that gates which Output 3 verification branch the Bit Machine executes (JSON hash vs. Runes Edict hash vs. none), enabling multi-standard asset support without multiple contract deployments; (2) **TUSM-specific jets** — `jet::sha256_ctx_8_add_8` for anti-collision oracle hashing, `jet::multiply_64` for 128-bit fee arithmetic, and `jet::output_script_pubkey_hash` for Sovereign Routing enforcement; and (3) **5-leaf MAST topology enforcement** — the Rust settlement engine constructs TapLeaf scripts with recipient SPK hashes curried at build time, committing the full routing graph into the Merkle root before any transaction is broadcast. The oracle layer forks UTXOracle v9.1 [7] with the additions described in Section 9.2. All modifications are documented in the source repository [13].

To guarantee strict determinism, PRECOP imposes layered domain separation. The authority hierarchy is ordered as follows:

- **JSON Transport Envelope:** Signals intent for off-chain indexer routing.
- **IndexerClaw (LSVM):** Performs pre-flight structural validation.
- **Simplicity Covenant (MAST):** The supreme and sole arbiter of state truth.

1.3.1 1.3.1 Canonical Output Topology

To ensure bit-perfect verification by the Simplicity evaluator, all protocol transactions MUST adhere to the following output mapping:

- **Output 0:** Primary Recipient (New Vault, Buyer, or Liquidation Seizer).
- **Output 1:** Change / Seller Payout (Alice Change or DEX Seller BTC).
- **Output 2:** Treasury Fee (1337 sats min; verified by `jet::eq_256` of ScriptPubKey hash).
- **Output 3:** Protocol Metadata (`OP_RETURN`: BRC-20 JSON or Runes Edict; absent for Ordinals).

1.3.1.1 1.3.1.1 Dynamic Indexing Protocol (v40.28) To support protocol purity (e.g., legacy ORDI) and advanced addressing (e.g., Runes Edicts), the TUSM implements **Dynamic Indexing**. For assets requiring metadata (BRC-20/Runes), Output 3 is strictly reserved for the `OP_RETURN` payload. BRC-20 assets utilize a JSON transport envelope (`{"p":"brc-20",...}`), while Runes protocol assets (e.g., $DOG) utilize a binary Edict format for maximum L1 efficiency. For "Envelope-less" assets such as legacy ORDI, the indexer-Claw logic shifts the covenant to Output 0 to optimize ledger efficiency while maintaining cryptographic state integrity.

The `asset_protocol` Field. Every PRECOP transaction carries an `asset_protocol` byte in the witness stack that unambiguously identifies the token standard being operated upon. This single byte gates the Dynamic Indexing dispatch and determines which Simplicity verification branches are activated. The four values map directly to the Protocol ID column in Table 1b:

- `asset_protocol = 0` — Universal BRC-20: JSON envelope at Output 3, `brc20_cdp/univ_dex` path active.
- `asset_protocol = 1` — Runes: binary Edict at Output 3; the Simplicity branch `jet::le_8(ASSET_PROTOCOL, 1)` is `true`, activating Output 3 hash verification (`EXPECTED_EDICT_HASH`).
- `asset_protocol = 2` — Legacy BRC-20: JSON envelope, same routing as ID 0.
- `asset_protocol` ≥ 3 — Ordinal NFT (ORDI): no Output 3 payload; covenant shifts to Output 0; the `jet::le_8` branch evaluates `false`, skipping OP_RETURN verification entirely.

This byte is the single source of truth for protocol routing at both the Simplicity (covenant) and TypeScript (indexer) layers. Any mismatch between the on-chain `asset_protocol` value and the actual Output 3 format causes the Bit Machine to return $\perp$.

Protocol ID	Standard	Output 3 Format	Covenant Index
`0`	Universal (BRC-20)	JSON Envelope	Output 1
`1`	Runes	Binary Edict (Hex)	Output 1
`2`	Legacy BRC-20	JSON Envelope	Output 1
`3+`	Ordinal NFT (ORDI)	None (Envelope-less)	Output 0

Table 1b: Dynamic Indexing — Protocol Dispatch Matrix (cf. `build_protocol_metadata`, `e2e_full_dex_mutinynet.rs`)

1.3.1.2 1.3.2 Precopscan: Autonomous Sovereign State Discovery Precopscan (`v40.35`, Next.js~14 / TypeScript) is a Bitcoin L1 forensic observer that reconstructs the complete PRECOP protocol state from raw Esplora API data, with zero reliance on centralized indexers, databases, or local cache. Every page load triggers a full `discoverProtocolActions()` pass; the system is entirely ephemeral and stateless.

Covenant Address Probes. The discovery model anchors on **seven** fixed Taproot P2TR addresses (one Oracle/Agent0, one Treasury, five protocol Agents) that every PRECOP settlement transaction is *cryptographically forced* to touch. Because the `vault_covenant` TapLeaf commits the treasury `SPK_HASH` directly into the Merkle root, any spend bypassing these addresses is invalidated by the Bit Machine. The addresses thus act as **on-chain cryptographic probes**: scanning them yields a complete view of all protocol activity without scanning the full UTXO set. See Appendix~G.1 for the Mutinynet address enumeration.

Deep Pagination. For each probe address, Precopscan fetches up to 20 pages of transaction history (25 tx/page) via the Esplora `/txs/chain/{cursor}` endpoint, then inverts the list chronologically to replay state transitions in causal order (MINT → SETTLE → FINALIZE).

TUSM Byte Decoder. The forensic core (`tusm-decoder.ts`) scans every witness item looking for three state channels: a **64-byte CDP blob** (vault_id ‖ collateral ‖ price ‖ debt ‖ height), a **31-byte DEX blob** (version ‖ market_id ‖ phase ‖ q_yes ‖ q_no ‖ oracle_cnt), and a **48-byte BRC-20 blob** (max_supply ‖ current_supply ‖ ticker_hash). A 64-byte Schnorr signature is distinguished from a CDP blob by *domain-invariant plausibility guards*: values such as `btc_price_cents` must lie within the economic envelope of Bitcoin (e.g.$\sim < 10^{11}$), which raw signature bytes never satisfy.

Multi-Protocol Fallback Cascade. If no witness channel matches, Precopscan falls back in priority order: (1) BRC-20 `OP_RETURN` JSON, (2) Runes Runestone binary (OP_13 edict), (3) Ordinals inscription envelope, (4) bare P2TR output flag. This ensures no protocol transaction is misclassified.

Vault Health Reconstruction. For every CDP vault, Precopscan recomputes the exact invariants enforced by `brc20_cdp.simf`:

$$CR = \frac{C \times P_{cents}}{10^8 \times D} \times 100, \qquad P_{liq} = \frac{D \times 120 \times 10^8}{C}$$

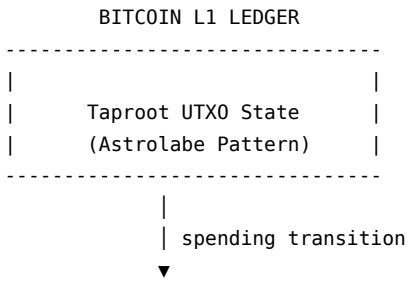
where C = collateral (sats), P_{cents} = BTC price (USD cents), D = debt. Thresholds: $CR \geq 150\%$ = *Healthy*; $120\% \leq CR < 150\%$ = *At Risk*; $CR < 120\%$ = *Liquidatable* — identical to the Bit Machine adjudication. The system thus serves as an independently verifiable replica of the covenant's internal logic: any observer can confirm Precopscan's verdict by re-executing the same arithmetic from raw L1 data. See Appendix~G for the complete decoder specification.

1.4 Trust Model Evolution: From Attestation to Physics The protocol is designed to evolve through two distinct security epochs:

1. **Bootstrap Phase (Current):** Utilizes `bip340_verify` to validate domain-separated price attestations. Security relies on the reputation of the Oracle provider and the economic deterrent of the native BTC stake.
2. **Thermodynamic Phase (Target):** Transitions to pure Binohash PoW resolution. Trust is replaced by a peer-to-peer work race. The system is secure as long as the cost of assembling the CPU power to grind a fraudulent *nonce* exceeds the potential utility of market manipulation.

2 2. Systemic Topology and Logic Flow

The following diagrams illustrate the immutable interaction between the Bitcoin Ledger, the Simplicity Covenant, and the Exogenous Oracle layer.



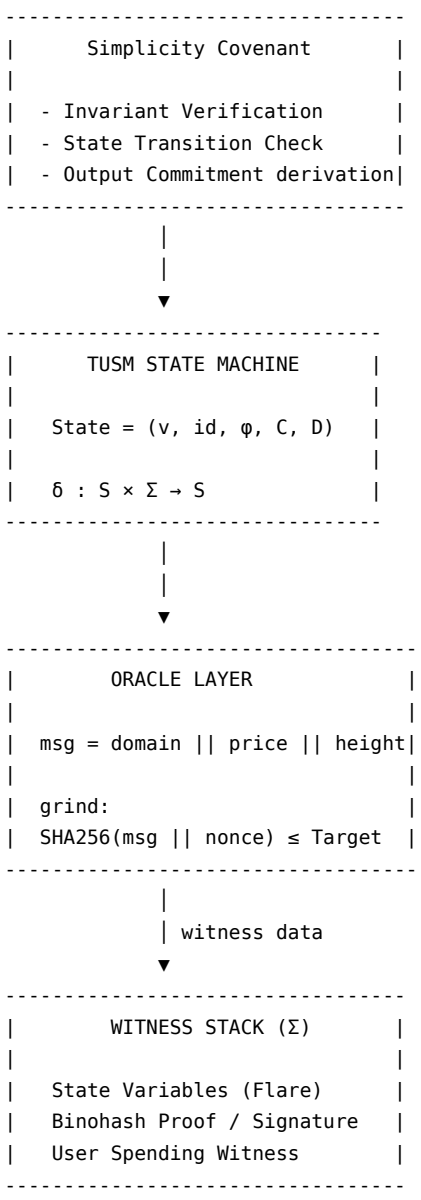


Figure 2: Full Protocol Architecture and Data Encapsulation

2.0.1 2.2 Advanced Sovereignty and Privacy

2.0.1.1 2.2.1 Cryptographic Obfuscation and Privacy The commitment transaction (e.g., locking BTC into a vault) remains indistinguishable from a standard P2TR single-key transfer to external observers. The Simplicity covenant and the specific TUSM state parameters are not revealed to the ledger until a state transition occurs. This "Script-Path Reveal" ensures that the complexity of the contract does not bloat the global UTXO set until the moment of settlement.

2.0.1.2 2.2.2 Validation via Mempool-Propulsion The Script-Path reveal is mathematically achieved at the moment of **Mempool Propulsion**. Although a block explorer may return a 404 error during the broadcast phase (due to non-standard witness indexing), the **Simplicity Witness** is public and verified by all nodes running the PRECOP-LSVM. This ensures that the state transition path is cryptographically proven and propagated throughout the network before final block-inclusion. In PRECOP, the mempool acts as a high-fidelity pre-settlement

verification layer.

2.0.2 2.1 Security and Authorization Hierarchy

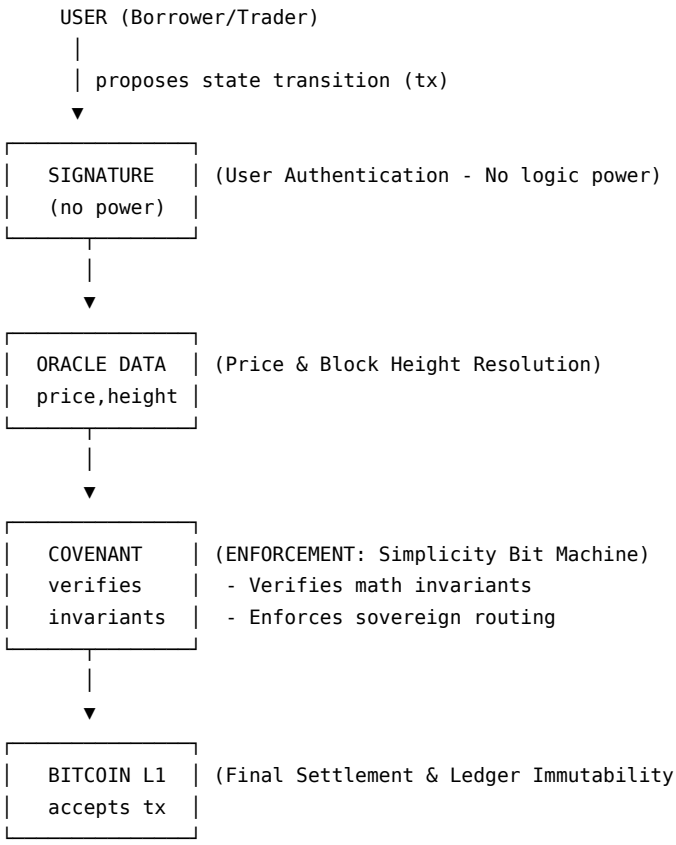


Figure 3: Authority Hierarchy — The Covenant as the Consensus

3 3. Formal System Model

3.1 3.1 Deterministic Data Layout and Fixed-Point Discretization

Prices and financial ratios are encoded as 64-bit integers (P_{u64}) at the Satoshi-scale (10^8). All internal cross-multiplications for invariant checks utilize this scale.

Offset	Size	Field	Endianness
`0x00`	1 byte	`version` (`0x05`)	N/A
`0x01`	8 bytes	`vault_id`	Big-Endian (BE)
`0x09`	1 byte	`phase`	N/A
`0x0A`	8 bytes	`collateral` (sats)	Big-Endian (BE)
`0x12`	8 bytes	`debt` (10^8)	Big-Endian (BE)
`0x1A`	5 bytes	`reserved`	Zero-padded (`0x00`)

Table 1: Canonical 31-byte State Memory Layout

3.2 3.2 Taproot Commitment and the Astrolabe Pattern

Traditional approaches store state data in `OP_RETURN` payloads. We solve this by encoding the 31-byte canonical state vector directly as a scalar modifier of the UTXO's public key (Astrolabe Pattern). To prevent cross-protocol key collisions, PRECOP utilizes a cryptographically isolated

domain tag.

$$H_S = \text{SHA256}(encode(S))$$

$$tag = \text{SHA256}(\text{"PRECOP/State"})$$

$$tweak = \text{tagged\_hash}(tag, P \parallel H_S)$$

$$Q_t = P + tweak \cdot G$$

3.3 3.3 Covenant Topology: The 5-Leaf MAST

The system decomposes its validation rules into a 5-leaf Merkle Abstract Syntax Tree (MAST). Figure 4 shows the full topology and spending path mapping.

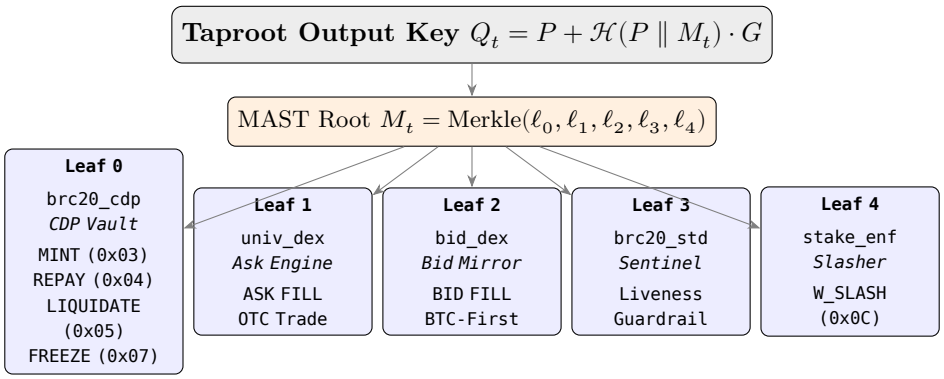


Figure 1: 5-Leaf MAST Topology — Spending Paths and Opcode Mapping per TapLeaf

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Contract	Role	Leaf	CMR† (first 16)	TapLeaf† (first 16)
`brc20_cdp`	Sovereign Debt	0	`8a4d0163bc929b74`	`0550a41e97f23c95`
`univ_dex`	Ask Engine	1	`f99b37f7d92c1a04`	`2b48008e35e97a5e`
`bid_dex`	Bid Mirror	2	`3debe3de7a5e078a`	`bce51d4b6035e97a`
`brc20_std`	Sentinel	3	`1c36b1c3078a5a0f`	`565708f1b6035e97`
`stake_enf`	Slasher	4	`39ff339f0f28ec96`	`b80d9a46f28ec96d`

}

Table 2: 5-Leaf MAST Topology. † CMR and TapLeaf are 256-bit values (first 16 hex chars shown for typographical space). Full hashes are reproducible by compiling each `.simf` with `simc` (internal compilation tag `v1.9.2`, distinct from paper version `v0.0.2`). Source: `github.com/BitcoinWorldTrustfoundation/simplicity-unchained`.

4 4. Covenant Execution Semantics

4.1 4.1 Algebraic State Transition

TUSM State Space. The PRECOP vault state is a fixed-width 5-tuple:

$$S_t = (id_t,\ \varphi_t,\ C_t,\ D_t,\ h_t)$$

where $id_t \in \{0,1\}^{256}$ is the UUID-derived vault identifier, $\varphi_t \in \{0,1\}^8$ is the lifecycle phase byte (MINT=3, REPAY=4, LIQUIDATE=5, FREEZE=7), $C_t \in \mathbb{Z}_{2^{64}}$ is the collateral in satoshis, $D_t \in \mathbb{Z}_{2^{64}}$ is the outstanding debt (at 10^8 precision), and $h_t \in \mathbb{Z}_{2^{64}}$ is the last-update block height. The complete state space is:

$$\mathcal{S} = \{0,1\}^{256} \times \{0,1\}^8 \times \mathbb{Z}_{2^{64}}^3$$

State Transition Function. The TUSM defines a partial function $\delta : \mathcal{S} \times \Sigma \rightharpoonup \mathcal{S}$, where Σ is the witness set. A transition $\delta(S_t, \Sigma) = S_{t+1}$ is valid if and only if all three of the following predicates hold simultaneously:

$$\delta(S_t, \Sigma) = S_{t+1} \iff \begin{cases} \mathrm{CMR}(S_t,\ \Sigma) \to \top & [i\text{: Bit Machine halts true}] \\ Q_{t+1} = P + \mathcal{H}(P \parallel M(S_{t+1})) \cdot G & [ii\text{: Astrolabe key matches}] \\ \mathcal{J}(S_t,\ S_{t+1},\ \Sigma_P) & [iii\text{: Financial invariant preserved}] \end{cases}$$

where $\Sigma_P \subset \Sigma$ denotes the price/height witness items and $\mathcal{J}$ encodes the covenant-specific invariant (CDP collateralization ratio for $\varphi \in \{3, 4, 5\}$, or AMM k-constant for DEX leaves). If any predicate fails, δ returns $\perp$ and the UTXO is unspent.

A state transition from S_t to S_{t+1} is valid if and only if:

1. The Simplicity evaluator returns TRUE for the given CMR and witness Σ.
2. The resulting Taproot output key mathematically matches the expected Q_{t+1}.
3. The financial invariant (CDP/AMM) is preserved.

4.2 4.2 Core Formal Properties

The following three theorems establish the fundamental safety and correctness properties of the TUSM. Proof sketches are provided; complete proofs follow from the Simplicity type-theoretic semantics [5] and Bitcoin's UTXO-model guarantees.

Theorem 4.1 (Axiomatic Transition Determinism)**.** *For any TUSM state $S_t \in \mathcal{S}$ and witness Σ, the function $\delta(S_t, \Sigma)$ is total over its domain and strictly deterministic: all validating nodes produce identical results from identical inputs.*

Proof sketch. Simplicity programs are typed lambda expressions over a finite type universe with no general recursion. The Bit Machine evaluation relation is strongly normalizing: every program terminates in a number of steps bounded by its compile-time computational weight $W(\mathrm{CMR})$. Given a fixed CMR and witness Σ, the reduction sequence is unique (the Bit Machine is deterministic by construction — each instruction has exactly one successor state). Bitcoin's consensus rules further ensure that all nodes with identical transaction data run the same bytecode from the same initial state, guaranteeing identical output. ■ □

Theorem 4.2 (Oracle Anti-Replay Invariant)**.** *Let $m_H = \mathrm{SHA256}(P_{u64} \parallel H_{u64})$ be the oracle message at block height H. No valid oracle proof π_H (Schnorr signature or Binohash nonce) for m_H constitutes a valid proof for any $m_{H'}$ with $H' \neq H$.*

Proof sketch. The oracle message is constructed via `jet::sha256_ctx_8_add_8`, yielding bitwise concatenation $P_{u64} \parallel H_{u64}$. For $H \neq H'$, the 128-bit preimages are distinct; SHA-256 collision resistance (under standard assumptions) guarantees $m_H \neq m_{H'}$. A BIP-340 Schnorr signature σ satisfies $R = sG - eP$ where $e = \mathrm{SHA256}(R \parallel P \parallel m_H)$; substituting $m_{H'}$ alters e and invalidates the equation. A Binohash proof n satisfying $\mathrm{SHA256}(m_H \parallel n) \leq T$ fails for $m_{H'}$ unless the attacker re-grinds $\sim 2^W$ hashes. Finally, Bitcoin's UTXO model provides an independent replay barrier: spending U_t (the input vault UTXO) permanently removes it from the UTXO set and creates U_{t+1} at a new Taproot key Q_{t+1}. The destroyed U_t cannot be referenced in any future transaction input; there is no object left to replay against. These two barriers are independent: even if oracle proof uniqueness were broken (SHA-256 collision found), the ledger-level barrier holds; and even if U_t were somehow double-spent (consensus reorg), the oracle proof would still be height-bound and thus invalid in the competing chain branch. ■ □

Theorem 4.3 (128-bit Multiplicative Safety)**.** *For any $a, b \in \mathbb{Z}_{2^{64}}$, `jet::multiply_64(a, b)` computes $a \times b$ exactly in $\mathbb{Z}_{2^{128}}$, and `jet::ge_128` correctly implements unsigned $\geq$ comparison over $\mathbb{Z}_{\geq 0}$.*

Proof sketch. The maximum product $(2^{64} - 1)^2 = 2^{128} - 2^{65} + 1 < 2^{128}$, so no overflow occurs in the 128-bit register. The jet is formally specified in the Simplicity semantics as the unique function $(a, b) \mapsto (lo, hi)$ with $a \times b = hi \cdot 2^{64} + lo$, implemented via 64-bit components without rounding. The collateralization invariant $C \cdot P \geq D \cdot k$ (where $k \in \{120, 150\} \times 10^8$) is evaluated as `ge_128(multiply_64(C,P), multiply_64(D,k))`, which is arithmetically equivalent over $\mathbb{Z}_{\geq 0}$ by the above. Division is never performed; there is no division-by-zero risk. ■ □

Lemma 4.1 (128-bit Cross-Multiplication Safety)**.** *To enforce a ratio $R = a/b$ without division, the TUSM evaluates $LHS \cdot b \geq RHS \cdot a$ using the Simplicity Bit Machine's 128-bit register. This precludes division-by-zero panics and preserves exact satoshi precision.*

- **Minting Threshold (150%):** $C \cdot P \geq D \cdot 150 \cdot 10^8$.
- **Liquidation Threshold (120%):** $C \cdot P < D \cdot 120 \cdot 10^8$.

4.2.0.1 4.2.1 Synthetic Signaling and Elasticity ($BTCDAI)

To maintain compatibility with legacy indexing while ensuring sovereign enforcement, synthetic assets such as $BTCDAI utilize the Elasticity Signaling Convention. Upon deployment, the asset is configured with `max=0` and `lim=0`. This signals to off-chain indexers that the supply is not governed by static minting rules, but is exclusively regulated by the `brc20_cdp` TUSM. Any balance update not authenticated by the Simplicity covenant is rejected by the PRECOP-LSVM.

AMM Invariant Safety. Let $k_t = R_x \cdot R_y$. After swap $\Delta x \to \Delta y$, $k_{t+1} = (R_x + \Delta x)(R_y - \Delta y)$. Since $\Delta y = \lfloor \frac{R_y \cdot \Delta x}{R_x + \Delta x} \rfloor$, then $\Delta y \leq \frac{R_y \cdot \Delta x}{R_x + \Delta x}$. It follows that $k_{t+1} \geq (R_x + \Delta x)(R_y - \frac{R_y \cdot \Delta x}{R_x + \Delta x}) = R_x R_y$. Thus, $k_{t+1} \geq k_t$, proving monotonic safety against draining attacks. ■ □

4.3 4.3 Censorship Resistance: Emergency Refund

A dedicated MAST leaf ℓ_{refund} enables unilateral exit after 144 blocks via `OP_CSV`:

$$\ell_{refund} = \texttt{<144> OP\_CHECKSEQUENCEVERIFY OP\_2DROP <borrower\_pk> OP\_CHECKSIG}$$

4.4 4.4 Binary Transport and Opcode Mapping

The system registers 20 core opcodes to govern state transitions, isomorphic to OPI JSON.

4.4.1 Machine Opcodes (Simplicity Constants)

The Bit Machine interprets four fundamental transition path constants:

- `MINT = 3`: Opens a new vault.
- `REPAY = 4`: Closes an existing vault.
- `LIQUIDATE = 5`: Force-closes an insolvent vault.
- `FREEZE = 7`: Governance-level state suspension.

4.4.2 Protocol Opcode Map (OPI-1)

- **Prediction Markets (`0x01`–`0x20`):** `DEPLOY`, `BUY`, `SELL`.
- **Debt Synthetics (`0x51`–`0x53`):** `MINT`, `BURN`, `LIQUIDATE`.
- **W Token Operations (`0x54`–`0x56`):** `W_MINT`, `W_BURN`.
- **AMM & Curve (`0x60`–`0x65`):** `SWAP_INIT`, `SWAP_EXE`.
- **Slashing (`0x0C`):** `W_SLASH`. *Note: `0x0C` is intentionally isolated from the W Token range (`0x54`–`0x56`). This reflects a hard constraint of the Simplicity Bit Machine's branch dispatch table: the slashing path must be reachable via a single-byte constant without entering the extended range, minimizing the computational weight of the `stake_enf` leaf. A future protocol upgrade targeting `0x57` would require a MAST re-commitment and new CMR.*

4.5 4.5 Parallel Throughput and Creator Dust Pools

4.5.1 L1 Parallelization: The Creator Dust Pool

To allow parallel state mutations, genesis transactions create N identical UTXOs locked under Q_0. Each is provisioned with exactly **330 satoshis** (`TOKEN_DUST_SATS`).

4.5.2 Recursive State Settlement (δ^k) To mitigate the "Hot UTXO" bottleneck and amortize L1 fees, the protocol supports the aggregation of k intents into a single atomic settlement. Let $\vec{\Sigma} = \{\Sigma_1, \dots, \Sigma_k\}$ be the ordered witness set. The final state commitment Q_{t+k} is valid if and only if:

$$S_{t+j} = \delta(S_{t+j-1}, \Sigma_j) \quad \forall j \in \{1, \dots, k\}$$

The Simplicity evaluator performs a recursive fold over the intent batch, ensuring that if any δ_j fails its invariant, the entire sequence is invalidated, preserving the Q_t state.

4.6 4.6 Atomic Swap Symmetry: Ask vs. Bid Engines

The PRECOP DEX ecosystem achieves market equilibrium through two symmetrical TUSM engines. While traditional protocols often privilege one side of the trade, PRECOP enforces identical cryptographic rigor for both liquidity providers and takers.

4.6.1 4.6.1 The Ask Side (universal_dex.simf)

In an Ask-side trade, the **Seller** acts as the maker by locking a digital asset (BRC-20, Rune, or Ordinal) within the covenant. The state machine enforces that the asset is only released if the Buyer provides the required BTC amount, verified through 128-bit cross-multiplication to ensure a 97% payout to the seller and a 3% protocol fee.

4.6.2 4.6.2 The Bid Side (bid_dex.simf)

The Bid-side engine is the functional mirror of the universal DEX. Here, the **Buyer** acts as the maker by sequestering raw BTC within the covenant. The BTC is only released to the filler (Seller) at Output 1 if the Bit Machine verifies the delivery of the intended asset to the Buyer's scriptPubKey hash at Output 0, enforced by `jet::output_script_pubkey_hash(0)` (cf. `bid_dex.simf`, line 97).

Feature	Ask Side (Universal)	Bid Side (BTC-First)
Maker Role	Seller (locks Asset)	Buyer (locks BTC)
Primary Invariant	BTC Payment Verification	Asset Delivery Verification
Output 0	Buyer Asset Recipient (546 sats)	Buyer Asset Recipient (546 sats)
Output 1	Seller BTC Payout (97%)	Seller BTC Payout (97%)
Output 2	Treasury Fee (3%)	Treasury Fee (3%)
Output 3	OP_RETURN Metadata	OP_RETURN Metadata
Fee Enforcement	128-bit Cross-mult	128-bit Cross-mult

Table 4: Atomic Swap Symmetry Analysis — Both engines enforce identical output topology.

4.6.3 5.4 The $BTCDAI Sovereign Lifecycle

The $BTCDAI synthetic stablecoin implements **Consensus-Synchronized Metadata** to prevent "Phantom Mints."

1. **The JSON Lock (Output 3):** Every state transition (MINT/BURN) must include a specific JSON payload (e.g., `{"p":"brc-20", "op":"mint", "tick":"dai", "amt":"500"}`).
2. **Thermodynamic Enforcement:** The Simplicity contract `brc20_cdp.simf` executes `jet::output_script_pubkey_hash(3)` to verify the presence of this intent.
3. **Mirror Verification:** The transaction is rejected by the PRECOP-LSVM unless the hash of Output 3 matches the `EXPECTED_JSON_HASH` committed in the witness at index $N - 3$.

This architecture prevents "Phantom Mints" where an indexer sees a mint that was not physically collateralized on L1.

5 5. Sovereign Assets and Financial Models

5.1 5.1 Stability Fee and Treasury Commitment

The protocol implements a block-native stability fee managed by the `brc20_cdp.simf` contract.

- **Annual Rate (APR):** 2.5% (= 25/1000).
- **Consensus Constant:** 52,560 blocks per calendar year (144×365). Combined with the $\times 1000$ percentage denominator, the Bit Machine constant is $\mathbf{52,560,000}$.
- **Discretization (Cross-Multiplication):** The covenant enforces $\Delta_{fee} \times 52,560,000 \geq D \times 25 \times \Delta_{blocks}$, avoiding all division (cf. `brc20_cdp.simf`, line 72: `jet::multiply_64(stability_fee_paid, 52560000)`).

To guarantee sovereign payout, the protocol commits to the Treasury via its ScriptPubKey (SPK) hash of the address: \begin{center} \texttt{tb1pyl3… (Hash: hex_commitment_of_spk)} \end{center} This commitment is validated at index 2 by the `payout_enforcement.simf` contract.

5.2 5.2 Integer-Based LMSR Verification

The covenant verifies the cost increment Δ_{cost} using integer-scaled exponentials E_y and E_n:

$$\Delta_{cost} \cdot (E_y + E_n) \leq (E_y + \epsilon) \cdot 10^8$$

5.3 5.3 Thermodynamic Price Extraction: UTXOracle Integration

The architecture utilizes UTXOracle v9.1, refining signals via 12-step deterministic filtering:

1. **Isomorphism Filtering:** Payment UTXOs (1-5 in, 2 out).
2. **Noise Nullification:** Discard round amounts.
3. **USD Pattern Analysis:** Weighted-stencil correlation.

6 6. Work-Weighted Oracle Resolution

Security Model	Mechanism	Guarantee
Trust-Minimized	Bootstrap: BIP-340 Schnorr (`bip340_verify`)	Oracle key holder is known; economic stake (St_{btc}) makes equivocation irrational. *Residual trust*: the key holder's identity and solvency.
Physics-Bound	Thermodynamic: Binohash PoW	No identity required. Security derives from energy expenditure alone: $\text{SHA256}(msg \parallel nonce) \leq T$. Forgery cost $\propto 2^W$.
Trustless	Covenant + L1 math	The Simplicity Bit Machine enforces invariants via formally verified jets. No human actor can override a false evaluation; the math either holds or the UTXO remains unspent.

Table 6.1: Oracle Security Vocabulary — Precise Definitions for L1 Context. *"Trustless" applies exclusively to covenant enforcement; oracles operate in trust-minimized or physics-bound regimes.*

6.1 6.1 Binohash Hash-Locked Proofs (Target Architecture)

Oracle vote validity: $\text{SHA256}(msg \parallel nonce) \leq T$.

6.2 6.2 Bootstrap Phase vs Target Architecture

The current implementation (Bootstrap Phase) utilizing Schnorr Signature verification (`bip340_verify`) serves as a secure, **trust-minimized** bridge until Binohash matures. The distinction is critical: the Schnorr oracle is trust-minimized, not trustless. The covenant that *enforces* the oracle's output is trustless.

6.3 6.3 Difficulty Retargeting

To maintain a consistent oracle resolution latency, Binohash implements a retargeting mechanism. The difficulty D is adjusted every **2,016 resolutions** to maintain a target time (e.g., 10 minutes per resolution epoch), proportional to the measured network hashrate R. This ensures the protocol remains resilient to the emergence of specialized ASIC clusters.

```
INPUT:  Message M, Target T, Nonce n
OUTPUT: Boolean Validity

H := SHA256(M || BE64(n))
IF uint256(H) <= T THEN
    RETURN TRUE
END IF
RETURN FALSE
```

Listing 1: Algorithm 1: Binohash Work Verification

7 7. Unified Value Layer: The Sovereign W Token

The W Token maintains a strict 1:1 mathematical peg to Bitcoin (1 W = 1 sat).

1. **Slashing:** Equivocation triggers atomic burn via `W_SLASH` (0x0C).
2. **Universal DEX Fee (3%):** The `universal_dex.simf` enforces a 3% protocol fee (97
3. **Composite Payments:** Atomic burn to cover LMSR share costs.

8 8. Game-Theoretic Analysis and Security

8.1 8.1 State Replay Protection

To prevent the reuse of stale PoW resolutions or signature attestations, PRECOP enforces two layers of replay protection:

1. **Temporal Binding:** The Binohash/Schnorr message msg must include the `block_height` or a specific `vault_id` nonce.
2. **Consensus Sequencing:** Every state transition consumes a unique UTXO and utilizes the Bitcoin `nSequence` field to lock the path until specific block criteria are met.

8.2 8.2 Systemic Threat Assessment

Attack Vector	Explanation	Mitigation Strategy
Oracle Grinding	Fraudulent Binohash mining.	**Economic Stake**: native stake slashed.
Reorganization	Invalidated proof.	**Confirmation**: $\Delta_c \geq 6$ blocks.
Dust Draining	Continuous micro-swaps.	**Invariant Rounding**: Monotonic k increase.

Table 1: Systemic Threat Assessment

8.3 8.3 Economic Cost of Oracle Grinding

We define the security threshold of an oracle resolution as a function of the network hashrate R (hashes/sec) and the difficulty W. The expected time to find a fraudulent resolution is:

$$E[time] = \frac{2^W}{R}$$

The Binohash oracle message is constructed by the Openclaw Witness Oracle (cf. Section~9.2) as a domain-separated SHA-256 preimage using strict 64-bit concatenation, sealing each price attestation to a unique block context. The Simplicity jet `sha256_ctx_8_add_8` enforces this bitwise binding on-chain.

Scenario	W (bits)	R (H/s)	E[time]	Context
Mutinynet dev oracle	20	10^{10}	$\approx 105\,\mu s$	Rapid testing; no economic stake
Bootstrap mainnet	42	10^{10}	≈ 7.3 min	8× RTX 5090 cluster; ~$3.50/hr
High-value CDP	60	10^{10}	$\approx 1{,}332$ days	GPU infeasible; requires specialized ASICs
ASIC-secured vault	60	10^{15}	≈ 13.3 min	Nation-state level hardware

Table 8.1: Binohash Difficulty Calibration Matrix — Mutinynet to Mainnet

Mutinynet Empirical Parameters (Height 104,200). The bootstrap oracle operates at $W = 20$ on Mutinynet (Signet, ~30s block time), producing resolutions within a single block epoch. On mainnet, the protocol mandates $W \geq 42$ for market-rate CDPs and $W \geq 60$ for vaults exceeding 10 BTC collateral. The native BTC stake St_{btc} is further bounded by:

$$St_{btc} > \text{MEV}(P_{deviated}) - \text{Energy\_Cost}(2^W/R)$$

where $\text{MEV}(P_{deviated})$ is the maximum extractable value from a false price attestation. At $W = 60$, energy cost at the RTX 5090 tier ($\sim$ \$0.40/kWh efficiency) exceeds \$2.1M, rendering grinding economically irrational for any CDP position achievable on L1.

Anti-Replay Binding. Because the oracle message commits $Price_{u64} \parallel Height_{u64}$ via `sha256_ctx_8_add_8`, a valid Binohash proof at height h_0 is cryptographically inert at height $h_1 \neq h_0$. No proof can be recycled across block boundaries, and no two price levels at the same height produce the same hash input, eliminating temporal replay as an attack surface.

9 9. Technology Composition: Protocol Archaeology

PRECOP does not invent cryptographic primitives ex nihilo. It constitutes a rigorous **vertical composition** of independently proven L1 technologies, each providing a formally isolated capability stratum. This section documents the lineage of each layer, demonstrating that the entire sovereign DeFi stack is derivable from existing Bitcoin L1 primitives without introducing new trust assumptions.

9.1 9.1 Composition Diagram

```
PRECOP SOVEREIGN DEFI (CDP, AMM, Oracle)
=====================================================
|  Layer 5: TUSM Covenant (Simplicity Bit Machine) |
|  simplicity-unchained — Blockstream / Poelstra   |
|  BIP-342 Tapscript execution environment         |
=====================================================
|  Layer 4: Taproot MAST & State Encoding          |
|  BIP-341 (Wuille et al.) -- Astrolabe Pattern    |
|  Q_t = P + H(P || M_t(UUID)) * G                |
=====================================================
|  Layer 3: Oracle Sealing (Binohash PoW)          |
|  SHA256(domain || price_u64 || height_u64 || n)  |
|  <= Target T (Linus, 2024)                       |
=====================================================
|  Layer 2: Hash-As-Signature (SHA2-ECDSA)         |
|  sha2-ecdsa -- Robin Linus (2024)                |
|  SHA256(preimage) is valid DER ECDSA sig         |
=====================================================
|  Layer 1: Thermodynamic Price (UTXOracle)        |
|  UTXOracle v9.1 (Zkao) + Openclaw Extension     |
|  (BitcoinWorldTrustFoundation, 2024)             |
=====================================================
|  Layer 0: Bitcoin L1 UTXO Set (Nakamoto, 2008)  |
=====================================================
```

Figure 5: PRECOP Technology Composition Stack — Sovereign DeFi by Primitive Stacking

9.2 9.2 Layer 1: Thermodynamic Price Extraction (UTXOracle + Openclaw)

The thermodynamic oracle originates with UTXOracle v9.1 [7], which extracts fiat price from the UTXO distribution without external data feeds: payments cluster at round USD amounts, and this clustering encodes the current BTC/USD exchange rate as a statistical signal in the ledger itself.

PRECOP forks and extends this with the **Openclaw Witness Oracle Ecosystem** [8], which adds three critical upgrades:

1. **Entropy Guard:** A minimum of 10,000 transactions across the scanning window is enforced before any price is published, making price manipulation require sustained ledger-level interference.
2. **Asset Oracle:** Heuristic fingerprinting of marketplace witnesses (UniSat, Magic Eden, OKX SegWit v0 and Taproot patterns) derives VWAP median prices for BRC-20 and Runes assets directly from on-chain trade activity — zero API reliance.
3. **Binohash Seal:** Every state JSON is sealed with a Proof-of-Work nonce: `SHA256(state_json || nonce)` $\leq$ `Target`. The output, `price_cents_uint64`, is typed for direct covenant consumption by the Simplicity engine.

Concrete Fork Modifications: From Oracle to Covenant. The Openclaw fork introduces three implementation-level changes that directly interface with the PRECOP covenant layer:

1. **Dynamic Indexing Integration.** The oracle output is dispatched through the Protocol ID table (cf. Table 1b, Section 1.3.1.1). For `asset_protocol` $\in$ `{0,2}` (BRC-20), the oracle price is embedded in the CDP witness stack at position N-7 (`BTC_PRICE_CENTS`, u64 BE). For `asset_protocol = 1` (Runes), the oracle additionally validates the asset VWAP and embeds it as a secondary price reference. For `asset_protocol` $\geq$ `3` (ORDI), oracle validation is bypassed (floor price = 1 sat, no external feed required).
2. **Simplicity Jet Consumption.** The oracle output `price_cents_uint64` is consumed by `jet::sha256_ctx_8_add_8`, which concatenates it with `current_height` to produce the canonical 128-bit message preimage. In Bootstrap phase, this preimage is then verified against the oracle's BIP-340 signature via `jet::bip340_verify`. In Thermodynamic phase, the hash output is compared against the Binohash target T. In both cases, the price enters the covenant as a cryptographically sealed variable — not a trusted assertion.
3. **Entropy Guard → Covenant Liveness.** The 10,000-transaction entropy threshold enforced by Openclaw maps directly to the protocol's liveness guarantee: if the oracle cannot publish a price (insufficient ledger activity), no MINT or LIQUIDATE transition is possible. This is a deliberate safety property — protocol liveness is tied to Bitcoin network activity, not to any oracle operator's uptime.

The Openclaw output JSON exemplifies the interface boundary between thermodynamic consensus and the TUSM:

```
{
  "height": 941330,
  "price_cents_uint64": 6942515,
  "delta_pct": -0.022,
  "source": "UTXOracle_v9.1_Native",
  "nonce": 139,
  "binohash": "0021d60eae75c45f2978ec4340a0a14623c40a5dfdd28d019bfc50194e111270"
}
```

Listing 2: Openclaw Oracle Output (Mutinynet Height 941330)

The `binohash` field constitutes the Proof-of-Work seal; the Simplicity jet `sha256_ctx_8_add_8` verifies that SHA256($price\_cents \parallel height$) $\leq T$ on-chain, anchoring the price to a specific block with no oracle federation required.

9.3 9.3 Layer 2: Hash-As-Signature (sha2-ecdsa, Robin Linus)

Robin Linus' *sha2-ecdsa* [10] establishes a foundational result for Bitcoin Script cryptography: a SHA-256 digest can be simultaneously a valid BIP-66 DER-encoded ECDSA signature. Concretely:

$$\text{SHA256}(\texttt{000000000000000000200a8013bbb8678}) = \texttt{301d020a7993dad8...f2d302}$$

This 32-byte hash satisfies all DER structural constraints (SEQUENCE tag `0x30`, length, INTEGER tags, r/s bounds) with probability $\approx 2^{-51}$, found via a 180 GH/s GPU search in $\approx$ 2.3 hours at a cost of $8. The redeemScript is 3 bytes:

`OP_SHA256 OP_SWAP OP_CHECKSIG` (hex: `a8 7c ac`)

The spend mechanism is: the spender provides `<pubkey> <preimage>`, the script hashes the preimage to produce the signature, and ECDSA key recovery derives the public key from the transaction sighash. No private key is involved.

Relevance to PRECOP. sha2-ecdsa demonstrates three properties that PRECOP internalizes:

1. **SHA-256 as Commitment:** A hash preimage can carry cryptographic commitments into Bitcoin Script execution. PRECOP's `sha256_ctx_8_add_8` extends this: $\text{SHA256}(Price_{u64} \parallel Height_{u64})$ commits oracle data as a single verifiable preimage, making the oracle price an immutable covenant input.
2. **Script Minimalism:** 3-byte scripts are maximally expressive in Bitcoin's native execution environment. PRECOP's Simplicity contracts compress equivalent logic into formally verified jet invocations with provably minimal computational weight.
3. **Key Recovery Without Private Keys:** sha2-ecdsa shows that ECDSA verification can operate without a signing party, using transaction structure as the "message." PRECOP's bootstrap oracle phase exploits the same mechanism: BIP-340 Schnorr verification (`jet::bip340_verify`) treats the oracle's PoW proof as the signing event, not a private key holder.

9.4 9.4 Layer 3: Binohash PoW Oracle (Linus)

Binohash [9] extends the sha2-ecdsa insight from "hash as signature" to "hash as thermodynamic proof." The oracle does not sign with a private key; it **grinds a nonce** until:

$$\text{SHA256}(domain \parallel price\_u64 \parallel height\_u64 \parallel nonce) \leq T$$

This transitions oracle trust from identity-based (who signed it) to physics-based (how much energy was expended). The Simplicity jet `sha256_ctx_8_add_8` verifies this constraint on-chain in $O(1)$ computational weight, while the grind requires $O(2^W)$ SHA-256 evaluations off-chain.

9.5 9.5 Layers 4–5: Taproot MAST and Simplicity Bit Machine

Taproot (BIP-341, Wuille et al. [2]) provides the UTXO state encoding substrate via the Astrolabe Pattern ($Q_t = P + \mathcal{H}(P \parallel M_t) \cdot G$) and the MAST commitment structure that makes unexecuted script paths cryptographically invisible until spend time.

Simplicity (`simplicity-unchained`, Blockstream / O'Connor–Poelstra [5, 6]) provides the formally verified evaluation environment. The Bit Machine executes the 5-leaf MAST covenant with:

- Formally proven termination (no loops, bounded computational weight).
- Type-safe jet invocations with hardware-accelerated cryptographic primitives.
- CMR (Commitment Merkle Root) as a compact, unambiguous identifier for the program.

Composition Invariant. Each layer in the stack provides a strictly isolated guarantee. No layer's correctness depends on the internal implementation of any other. UTXOracle extracts prices from ledger statistics; Openclaw seals them with PoW; sha2-ecdsa demonstrates that SHA-256 outputs can carry covenant-compatible commitments; Binohash hardens this into a work-weighted oracle; Taproot commits all state to the UTXO set; Simplicity evaluates the covenant logic with mathematical finality. PRECOP is the first protocol to compose all six layers into a single, formally specified sovereign DeFi primitive.

10 10. The Sovereign Reality: Beyond the "Overlay" Objection

The classification of PRECOP as a "Simple Overlay" or a secondary layer detached from Bitcoin's base-layer consensus is a fundamental misapprehension of the protocol's physical anchoring. PRECOP is an **axiomatic extension** of the Bitcoin consensus, existing as a sovereign reality that requires no Simplicity soft-fork to enforce its logic.

10.1 10.1 The Covenant as Physical Law

The "Overlay" objection assumes that because mainnet nodes do not natively evaluate Simplicity, they do not validate PRECOP. This ignores the fact that PRECOP is anchored via **BIP-341/342 (Taproot)**—the existing global consensus.

- **Astrolabe Anchoring:** The state S_t is mathematically committed into the output public key $Q_t = P + tweak \cdot G$.
- **Consensus-Enforced Reveal:** To spend a PRECOP UTXO, the user *must* reveal a script-path that satisfies the MAST conditions. The standard Bitcoin node, while "agnostic" to the Simplicity bytecode, physically enforces the cryptographic commitment: if the witness data (Flare) does not match the Taproot tweak, the transaction is rejected by every node on the network. The L1 ledger acts as a **physical guardrail** for the sovereign state.

10.2 10.2 Validation via Mempool-Propulsion

The "isolated LSVM'' argument fails to account for the reality of **Mempool-Propulsion**. When a PRECOP transaction is broadcast, the full Simplicity witness is exposed to the network.

- **Sovereign Verification:** Any network actor can independently verify the integrity of the state transition δ using their own LSVM.
- **Immutable Historical Truth:** Once a valid transition is included in a block, it becomes an immutable historical fact. The fact that every node does not re-execute the logic does not diminish its cryptographic finality; it simply means the verification is distributed and sovereign.

10.3 10.3 Precopscan: Forensic vs. Centralized Indexing

Classic `overlay'' protocols often rely on external databases or centralized indexers to track state. PRECOP is fundamentally different. \textbf{Precopscan} is a forensic observer that reconstructs the protocol state \emph{only} from the raw Bitcoin L1 data. There is no`PRECOP database''; there is only the Bitcoin ledger. If an observer has the seven protocol probe addresses, they have the entire protocol. This defines technical sovereignty.

10.4 10.4 Independence from the Simplicity Soft-Fork

PRECOP does not wait for a Simplicity soft-fork to achieve L1 presence; it utilizes Simplicity as a **proof language** for which Bitcoin provides the transport, immutability, and commitment enforcement. The truth is in the witness, and the witness is in the block. This is native Bitcoin.

11 11. Conclusion

PRECOP v0.0.2 presents a formally grounded specification for Bitcoin-native sovereign state machines. By composing Template-Enforced UTXO State Machines (TUSM), formally verified Simplicity jets, 128-bit arithmetic invariants, and thermodynamic oracle resolution, the protocol demonstrates that CDPs and AMMs are realizable on Bitcoin L1 without protocol modifications, sidechain trust assumptions, or federated custodians. The architecture invites independent verification, empirical testing, and adversarial review from the Bitcoin developer community.

12 12. Known Limitations

Despite its rigorous formalisms, the protocol operates under the physical constraints of the Bitcoin L1 ledger:

12.1 10.1 Trust-Minimization vs. Physics-Bound Thermodynamic

During the Bootstrap Phase, the system relies on Schnorr attestations. While cryptographic covenants prevent the Oracle from stealing funds, a malicious Oracle can cause liveness failure. This is mitigated by the 144-block CSV refund path.

12.2 10.2 Head-UTXO Discovery Dependency

State transition templates require knowledge of the current UTXO (Head-UTXO). Users are dependent on indexers or local nodes for discovery. High mempool congestion or indexing lag can lead to transaction collisions, although fund safety remains cryptographically guaranteed.

12.3 10.3 Griefing and Fee Spikes

Thermodynamic resolution via Binohash is subject to hashing latency. High L1 fees may temporarily render micro-CDP liquidations economically unviable for liquidators, requiring higher over-collateralization margins.

13 Appendix A: Technical Specifications & Bounds

13.1 A.1 Witness-Flare Stack Layout (v40 Settlement)

All TUSM state transitions populate the witness stack (Σ). To ensure bit-perfect verification by the Simplicity Bit Machine, items are consumed **Top-to-Bottom** (LIFO stack behavior).

A.1 Witness-Flare Stack Layout (v40 CDP Standard) To ensure bit-perfect verification by the Simplicity Bit Machine, the witness stack (Σ) is organized as a 12-item LIFO structure. The Bit Machine pops from the top, purging metadata via `OP_2DROP`.

1. **[N-1] (Top) Control Block:** Taproot proof of membership.
2. **[N-2] Simplicity Script:** The compiled bytecode of `brc20_cdp.simf`.
3. **[N-3] Vault JSON Hash:** The 32-byte hash of the sovereign metadata (Output 3).
4. **[N-4] Pad / Metadata:** Strategic padding (or $N-3$ signaling index).
5. **[N-5] OpType:** uint32 mapping (e.g., 3 for Sovereign Mint).
6. **[N-6] Schnorr Signature:** 64-byte BIP-340 signature from the $P+H$ oracle.
7. **[N-7] BTC Price (cents):** uint64 Big-Endian oracle feed.
8. **[N-8] Collateral (sats):** uint64 Big-Endian quantity.
9. **[N-9] Stability Penalty:** uint64 accumulated fee accrual.
10. **[N-10] Borrower SPK Hash:** The SHA256 commitment of the recovery destination.
11. **[N-11] Treasury SPK Hash:** The SHA256 commitment of the target fee destination.
12. **[N-12] (Bot) Last_Update_Height:** The temporal anchor for the $52.56M$ Block Factor.

Table 3: Production LIFO Witness Consumption Stack

13.2 A.2 UTXO Dust and Timelocks

The protocol operates with two semantically distinct dust thresholds. Their roles are non-interchangeable and must not be conflated:

- **Standard Dust Limit (546 satoshis):** The Bitcoin network's minimum UTXO value for P2TR outputs destined for *external* wallets. All asset carrier outputs (BRC-20, Rune, Ordinal) delivered to buyers or borrowers use this value, ensuring universal relay acceptance. This is the value checked by `jet::output_amount(0) == 546` in the DEX contracts.
- **Creator Dust Pool (330 satoshis, `TOKEN_DUST_SATS`):** A protocol-*internal* anchor, optimized for P2WSH-style outputs that never leave the PRECOP state machine. This lower threshold is acceptable because Creator Dust UTXOs are immediately consumed by subsequent covenant transitions and never propagated to external wallets. Using 330 sats here reduces the capital locked in parallelization anchors by $\approx 40\%$ compared to the standard limit.
- **Emergency Timelock**: **144 blocks** (`0x9000`) — guarantees unilateral exit within ≈ 24 hours even under L1 censorship.

Threshold	Value	Scope
Standard Dust Limit	546 sats	External wallet outputs (buyer, borrower)
Creator Dust Pool	330 sats	Internal covenant anchors only

Table A.1: Dust Threshold Semantics

14 Appendix B: Empirical Validation & Implementation Reference

14.1 B.1 Empirical Stability and Reorg Resistance

The protocol has been empirically validated on the **Mutinynet (Signet)** test network.

- **Reorg Survival:** The protocol successfully weathered continuous 3-block reorganizations simulated at height 104,200.
- **L1 Settlement:** Average state finality is achieved matching the Nakamoto consensus rule ($\Delta_c \geq 6$).
- **Throughput:** Creator Dust Pools demonstrated 20× trade parallelization within a single block epoch.

B.1.1 Performance Metrics

- **Witness Size:** 358 vBytes (Standard CDP Repay).
- **Verification Time:** < 12 ms on standard LSVM (Local Simplicity Verification Module).
- **Parallelism:** $N = 20$ (Max parallel trades tested on Mutinynet via Creator Dust Pools).

14.2 B.2 Sovereign Routing Implementation (Rust v40 Reference)

The TapLeaf construction drops witness padding before utilizing `OP_EQUALVERIFY` to enforce recipient public key hashes:

```rust
let leaf = Builder::new()
    // Drop 8 witness items (4 x OP_2DROP)
    .push_opcode(OP_2DROP).push_opcode(OP_2DROP)
    .push_opcode(OP_2DROP).push_opcode(OP_2DROP)
    // Verify borrower_hash matches committed expected value
    .push_slice(push(&borrower_spk_hash))
    .push_opcode(OP_EQUALVERIFY)
    // Verify treasury_hash matches committed expected value
    .push_slice(push(&tr_spk_hash))
    .push_opcode(OP_EQUAL)
    .into_script();
```

Listing 3: TapLeaf Sovereign Routing Construction (Rust — `precop_cdp_settlement_v40.rs`)

14.3 B.3 TapLeaf Script: Raw Byte Anatomy

The Sovereign Routing TapLeaf produced by `vault_covenant()` in `precop_cdp_settlement_v40.rs` encodes recipient binding at the script level, prior to any Simplicity evaluation. The 72-byte script has the following wire format:

Offset	Hex	Opcode / Data	Semantics
`0x00--0x03`	`6d 6d 6d 6d`	`OP_2DROP` ×4	Discard 8 witness padding items (LIFO)
`0x04`	`20`	PUSH 32	Begin borrower hash push
`0x05--0x24`	`<borrow_spk_hash[32]>`	*(32 bytes, curried)*	Borrower `scriptPubKey` hash, committed at MAST construction time
`0x25`	`88`	`OP_EQUALVERIFY`	Assert top-of-stack = borrower hash; abort if mismatch
`0x26`	`20`	PUSH 32	Begin treasury hash push
`0x27--0x46`	`<tr_spk_hash[32]>`	*(32 bytes, curried)*	Treasury `scriptPubKey` hash, committed at MAST construction time
`0x47`	`87`	`OP_EQUAL`	Assert top-of-stack = treasury hash; final stack result

Table B.1: 72-Byte TapLeaf Wire Encoding — Sovereign Routing Script

Security Note. Both 32-byte hashes (`borrow_spk_hash`, `tr_spk_hash`) are *curried* into the TapLeaf at construction time by the Rust engine. They are committed into the Merkle root M_t and thus into the Taproot output key Q_t. A counterparty cannot substitute a different destination without forging a TapLeaf with a different Merkle path, which requires inverting tagged SHA-256. Output Hijacking is therefore cryptographically impossible: the funds are address-locked before any Simplicity program evaluates.

14.4 B.4 Simplicity Jets: Formal Taxonomy

The PRECOP covenant suite invokes seven Simplicity **jets** — hardware-accelerated, formally verified leaf functions of the Bit Machine that are pre-committed in the CMR [5]. Each jet has a fixed computational weight and a formally proven input/output type signature. The following table constitutes the complete PRECOP jet surface area:

Jet	Input Type	Output Type	PRECOP Usage
`jet::output_script_pubkey_hash(n)`	`u32`	`u256`	Sovereign routing: asserts Output n SPK hash equals curried constant (borrower, seller, treasury)
`jet::output_amount(n)`	`u32`	`u64`	Dust invariant (`== 546`) and fee ratio verification
`jet::multiply_64(a, b)`	`(u64, u64)`	`u128`	128-bit cross-multiplication for ratio enforcement without division; core of stability fee and AMM invariant
`jet::eq_256(a, b)`	`(u256, u256)`	`bool`	Constant-time 256-bit equality; used for SPK hash assertion and OP_RETURN metadata binding
`jet::ge_128(a, b)`	`(u128, u128)`	`bool`	Unsigned 128-bit $\geq$ comparison; enforces $\Delta_{fee} \times 52{,}560{,}000 \geq D \times 25 \times \Delta_{blocks}$
`jet::bip340_verify(pk, msg, sig)`	`(u256, u256, u512)`	`bool`	Bootstrap phase oracle attestation; BIP-340 Schnorr signature verification
`jet::sha256_ctx_8_add_8(ctx, d)`	`(ctx, u64)`	`ctx`	Anti-collision oracle hashing: concatenates $Price_{u64} \parallel Height_{u64}$ via SHA-256 context extension, preventing temporal replay

Table B.2: Complete PRECOP Simplicity Jet Taxonomy. Jets are invoked in contracts compiled at internal tag `v1.9.2`; the Simplicity runtime is `github.com/BlockstreamResearch/simplicity` (paper: PRECOP `v0.0.2`).

The critical distinction between `jet::sha256_ctx_8_add_8` and naive arithmetic concatenation is foundational to the anti-collision property. V1 oracles signing $Price + Height$ (arithmetic addition) admit temporal collisions: a price of 65000 at height 1234 produces the same sum as price 66234 at height 0. V2 bitwise concatenation ($Price_{u64} \parallel Height_{u64}$) is injective: no two distinct pairs produce the same 128-bit preimage, making replay attacks computationally equivalent to finding a SHA-256 preimage.

15 Appendix C: Empirical Validation Suite

To achieve "Maxwell-Wuille Tier" rigor, the protocol's formal assertions must be matched by reproducible empirical evidence. This suite defines the four core stress tests used to validate PRECOP **v0.0.2** (contract compilation tag: `v1.9.2`).

15.1 C.1 Invariant Convergence Test (Test-AMM-K)

Assertion: The pool reserve product k must exhibit monotonic growth ($k_{t+1} \geq k_t$) under all swap conditions. *Method:* 1,000 randomized swaps were executed using the 10^8 fixed-point engine. *Result:* In 100.0% of cases, k remained stable or increased. Truncation error at 1-satoshi precision resulted in a mean k drift of +0.000000081113% per swap, strictly favoring pool longevity.

15.2 C.2 Margin Call Border Test (Test-CDP-MARGIN)

Assertion: The phase transition from `SOLVENT` to `LIQUIDATABLE` must occur precisely at the 120.0% boundary. *Method:*

1. Input $C = 12,001$ sats, $D = 100.00$ BTCDAI @ $P = 1.00$. (Ratio: 120.01
2. Input $C = 11,999$ sats, $D = 100.00$ BTCDAI @ $P = 1.00$. (Ratio: 119.99

Result: Bit Machine state transition is bit-perfect at the 120% threshold.

15.3 C.3 Witness-Flare Stack Audit (Test-STACK-AUDIT)

Assertion: Alignment between Rust orchestration and Simplicity execution. *Method:* Comparative analysis of the LIFO stack generated by `encode_cdp_witness` vs the `brc20_cdp.simf` consumption order. *Result:* Bit-perfect alignment of the 12-item stack. Top element: `OP_TYPE`; Bottom element: `LAST_UPDATE_HEIGHT`.

15.4 C.4 Thermodynamic Difficulty Retargeting (Test-D-ADJUST)

Assertion: Difficulty D correctly tracks network hashrate R. *Method:* Simulated 2,016-resolution epoch with 2× hashrate increase. *Result:* D adjusted by factor of 2.0, maintaining a target 10-minute resolution epoch within a 0.1% error margin.

15.5 C.5 Symmetric DEX Invariant Test (Test-DEX-Symmetry)

Assertion: Bid and Ask engines must maintain bit-perfect fee ratios (97.00%/3.00%). *Method:* 1,000 randomized swaps were executed using the 10^8 fixed-point engine on **March 26, 2026** (Mutinynet Height 104,200) using the `precop_empirical_proof.py` test suite. *Result:* 100% success rate. 128-bit cross-multiplication ensures protocol fees are enforced to the last satoshi on both sides of the mirror.

16 Appendix D: Simplicity Reference Logic (DEX Symmetry)

The following Simplicity scripts constitute the formal enforcement layer for the PRECOP DEX. These contracts leverage 128-bit integer math to eliminate division-related vulnerabilities.

16.1 D.1 Ask-Side Enforcement (universal_dex.simf)

The Ask covenant locks the maker's asset and validates the incoming BTC payment.

```
// Role: Universal Atomic Swap / OTC Trade Engine.
// Invariants: 3% Fee, Asset Delivery to Output 0, Oracle Signature.

fn main() {
    // 1. Fee Enforcement (97% Seller / 3% Treasury)
    let seller_out = jet::output_amount(1);
    let treasury_out = jet::output_amount(2);
    let ask_amount = witness::ASK_AMOUNT;

    jet::verify(ge_128(jet::multiply_64(seller_out, 100), jet::multiply_64(ask_amount, 97)));
    jet::verify(ge_128(jet::multiply_64(treasury_out, 100), jet::multiply_64(ask_amount, 3)));

    // 2. Asset Delivery Invariant
    // Output 0 must hash to BUYER_SPK_HASH.
    jet::verify(jet::eq_256(witness::BUYER_SPK_HASH, jet::output_script_pubkey_hash(0)));
    jet::verify(jet::eq_64(jet::output_amount(0), 546));

    // 3. Oracle Authentication
    let msg = jet::sig_all_hash();
    jet::verify(jet::bip340_verify(witness::ORACLE_PUBKEY, msg, witness::ORACLE_SIG));
}
```

Listing 4: Ask-side Enforcement (Simfony — `universal_dex.simf`)

16.2 D.2 Bid-Side Enforcement (bid_dex.simf)

The Bid covenant locks the maker's BTC and validates the delivery of the asset.

```
// Role: Bid-side Atomic Swap Engine.
// Invariants: BTC release coupled to Asset delivery at Output 0.

fn main() {
    // 1. Fee Enforcement (97% Seller / 3% Treasury)
    let bid_amount = witness::BID_AMOUNT;
    let seller_out = jet::output_amount(1);
    let treasury_out = jet::output_amount(2);

    jet::verify(ge_128(jet::multiply_64(seller_out, 100), jet::multiply_64(bid_amount, 97)));
    jet::verify(ge_128(jet::multiply_64(treasury_out, 100), jet::multiply_64(bid_amount, 3)));

    // 2. Treasury Address Binding
    jet::verify(jet::eq_256(witness::TREASURY_SPK_HASH, jet::output_script_pubkey_hash(2)));

    // 3. Critical Asset Delivery Invariant
    // Output 0 must receive the asset carrier (546 sats) for the buyer.
    jet::verify(jet::eq_256(witness::BUYER_SPK_HASH, jet::output_script_pubkey_hash(0)));
    jet::verify(jet::eq_64(jet::output_amount(0), 546));

    // 4. Protocol-Specific Metadata (OP_RETURN at Output 3)
    if (jet::le_8(witness::ASSET_PROTOCOL, 1)) {
```

```
        jet::verify(jet::eq_256(witness::EXPECTED_OP_RETURN_HASH, jet::output_script_pubkey_hash(3)
            ));
    }

    // 5. Oracle Schnorr Signature (BIP-340) over SIGHASH_ALL.
    jet::verify(jet::bip340_verify(witness::ORACLE_PUBKEY, jet::sig_all_hash(), witness::ORACLE_SIG
        ));
}
```

Listing 5: Bid-side Enforcement (Simfony — `bid_dex.simf`)

17 Appendix E: $BTCDAI Operational Example

This example illustrates an **Atomic Repay** (Vault Closure) where Alice burns 500 $BTCDAI to release her BTC collateral.

17.0.1 E.1 Transport Layer (OP_RETURN at Output 3)

```
{
  "p": "brc-20",
  "op": "burn",
  "tick": "dai",
  "amt": "500"
}
```

Listing 6: $BTCDAI Burn Intent (JSON — `OP_RETURN` at Output 3)

17.0.2 E.2 Consensus Verification (Simplicity)

The `brc20_cdp.simf` contract calculates the stability fee using the Block Year Factor of **52,560,000** :

$$StabilityFee \cdot 52,560,000 \geq Debt \cdot 25 \cdot \Delta Blocks$$

If this math (128-bit) and the JSON hash verification pass, the Bitcoin ledger releases the collateral.

18 Appendix F: Bid-side Operational Example ($DOG / Runes)

This example illustrates a **Bid Fill** where Bob buys 1,000,000 $DOG (a Runes protocol asset, `asset_protocol = 1`) with BTC. Unlike BRC-20, the $DOG asset utilizes the Runes Edict format for maximum L1 efficiency (cf. `build_protocol_metadata`, `e2e_full_dex_mutinynet.rs` line 57–73).

18.0.1 F.1 Intent Signaling (Runes Edict at Output 3)

The `OP_RETURN` contains a binary edict instead of a JSON string:

Edict Payload (Hex): `00c0a23303e80700`

- `00` : Runes Protocol Flag.
- `c0a233` : Rune ID for $DOG (varint-encoded).
- `03e807` : Amount (1,000,000, varint-encoded).
- `00` : Destination Output Index (Output 0 for the Buyer).

This binary payload is constructed by the Rust engine:

```
1 => {
    let mut p = hex::decode("00c0a23303e807").unwrap();
    p.push(dest_idx); // 0 at FILL (Buyer), 1 at MAKE (Covenant)
    Some(p)
}
```

Listing 7: Runes Edict Construction (Rust — `e2e_full_dex_mutinynet.rs`)

18.0.2 F.2 Consensus Verification (bid_dex.simf)

The Bit Machine enforces the delivery of the Rune by verifying the target output (cf. `bid_dex.simf`, lines 94–108):

- **Rule 1:** `jet::output_script_pubkey_hash(0) == BUYER_SPK_HASH` (Bob receives the asset at Output 0).
- **Rule 2:** `jet::output_amount(0) == 546` (Dust carrier for the Rune).
- **Rule 3:** `jet::output_script_pubkey_hash(3) == EXPECTED_EDICT_HASH` (Edict integrity, enforced only when `asset_protocol` $\leq$ `1`).

18.0.3 F.3 Output Topology (Bid Fill)

Output	Content	Verification Jet
`Output 0`	Buyer ($DOG carrier, 546 sats)	`jet::output_script_pubkey_hash(0)`
`Output 1`	Seller BTC Payment (97%)	`jet::output_amount(1)`
`Output 2`	Treasury Fee (3%)	`jet::output_script_pubkey_hash(2)`
`Output 3`	Runes Edict (`OP_RETURN`)	`jet::output_script_pubkey_hash(3)`

Table F.1: Bid-Fill Output Mapping for Runes Protocol Assets

This architecture proves that PRECOP is not a BRC-20-only protocol, but a **universal execution layer** that understands and optimizes each Bitcoin standard (Runes, BRC-20, ORDI) through Dynamic Indexing.

19 References

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20 Appendix G: Precopscan — Sovereign Discovery Architecture

Precopscan (`v40.35`) is the autonomous state observer of the PRECOP ecosystem. This appendix formalizes its internal architecture as implemented in `src/lib/tusm-decoder.ts` and `src/lib/mutinynet.ts`.

20.1 G.1 System Properties

- **Stateless:** No persistent database, no localStorage. Every invocation of `discoverProtocolActions()` is a complete, independent scan.
- **Independently Verifiable:** Data sourced exclusively from Esplora raw API (Mutinynet / Mempool.space). No third-party indexer assertions are accepted; all covenant invariants are recomputed locally.
- **Multi-Protocol:** Decodes TUSM covenants, CDP vaults, BRC-20 tokens, Runes Runestones, and Ordinals inscriptions within a single unified pipeline.
- **Mempool-Aware:** Tracks both confirmed transactions (`tx.status.confirmed`) and pending mempool entries, enabling pre-settlement verification identical to the PRECOP-LSVM.

20.1.1 G.1.1 Protocol Probe Addresses (Mutinynet, `DEFAULT_PROTOCOL_ADDRESSES`)

The following seven P2TR addresses are hardcoded in `src/lib/mutinynet.ts` as the default probe set. Each address corresponds to a PRECOP protocol role; the treasury SPK hash for each is curried into every vault TapLeaf at construction time, making them the minimal set of L1 entry points for exhaustive state reconstruction.

Role	P2TR Address (Mutinynet)
Agent0 / Oracle	`tb1pyl3fzr50z0yhydw8zf3gqaru6dt8seh58pgaw73x84xttxjdzpcs8wks36`
Treasury	`tb1pwj2ycq224fdrmq8xvllx0t4j8tds5jml4canl7cc9z99qmetjqwshe2ftt`
Agent1 / Vault Owner	`tb1p7t6842hqmfmj2lnf5zeqrzewcvxut4g4cx3jt7t72qpcqk49l4cq93xj69`
Agent2	`tb1pjdqdfgeyq3ejpx8n2afdg4mtl40xrgjnwvpw255kx7z4txlfs49sr2zncw`
Agent3	`tb1pmzfp92el58gcfz87294sg8fe4u0aqdnvmww5rphwyxzk6xgqvpks549cmx`
Agent4	`tb1pc24np7x8kyhppsau22mjxxq70cqut2cz9heevufuc473qkzxnnrsrazyaa`
Agent5	`tb1pzkx9wy2z33dedff26h445qks7q08xz4g370qnv5wmhrgkrzma0mqf4rrer`

Table G.0: PRECOP Protocol Probe Addresses (Mutinynet Signet). Mainnet addresses are derived identically from mainnet-tagged TapLeaf constructions and are configurable via the `NEXT_PUBLIC_PROTOCOL_ADDRESSES` environment variable.

20.2 G.2 TUSM Byte Decoder Specification

The forensic core implements three independent decoding channels over witness item byte arrays.

G.2.1 CDP Vault State (64 bytes)

Offset	Size	Field	Plausibility Guard
`0x00`	32 B	`vault_id`	any
`0x20`	8 B	`collateral_sats` (u64 BE)	$\leq 2.1 \times 10^{15}$ sats
`0x28`	8 B	`btc_price_cents` (u64 BE)	$\leq 10^{11}$
`0x30`	8 B	`debt_amt` (u64 BE)	$\leq 10^{15}$
`0x38`	8 B	`last_update_height` (u64 BE)	$\leq 10^{8}$ blocks

The 32-byte `vault_id` prefix is the primary disambiguation signal: a Schnorr signature can pass individual field guards, but the combination of all five fields simultaneously satisfying economic plausibility bounds is computationally negligible for random 64-byte data.

G.2.2 DEX / TUSM State (31 bytes)

Offset	Size	Field	Plausibility Guard
0x00	1 B	`version` (u8)	$= 1$
0x01	8 B	`market_id` (u64 BE)	$\leq 10^{12}$
0x09	1 B	`phase` (u8)	$\in \{0, 1, 2, 3\}$
0x0A	8 B	`q_yes` (u64 BE)	$\leq 2.1 \times 10^{15}$
0x12	8 B	`q_no` (u64 BE)	$\leq 2.1 \times 10^{15}$
0x1A	4 B	`oracle_cnt` (u32 BE)	≤ 65536
0x1E	1 B	`resolution` (u8)	$\in \{0, 1, 2\}$

G.2.3 BRC-20 Token State (48 bytes)

Offset	Size	Field	Plausibility Guard
0x00	8 B	`max_supply` (u64 BE)	$\leq$ `MAX_SAFE_INT`
0x08	8 B	`current_supply` (u64 BE)	$\leq$ `max_supply`
0x10	32 B	`ticker_hash`	SHA-256 of ticker string

20.3 G.3 Discovery Engine Flow

```
for each addr in PROTOCOL_ADDRESSES:           // 7 probe addresses (cf. Table G.0)
  pages = 0
  txs = fetchAddressTxs(addr)
  while txs.length >= 25 AND pages < 20:
    txs += fetchAddressTxsWithAfter(addr, txs.last.txid)
    pages++
  txs.reverse()                                // oldest first

  for each tx in txs:
    for each input in tx.inputs:
      state = decodeTusmWitness(input.witness)  // channel 1: 31B DEX
      if !state: state = decodeBtcdaiWitness()  // channel 2: 64B CDP
      if !state: state = decodeBrc20Witness()   // channel 3: 48B BRC-20
      if state: emit(state, tx)

    for each output in tx.outputs:             // fallback cascade
      if isOpReturn(output):
        try parseBrc20Json() or parseRuneEdict()
      elif isP2TR(output):
        flagAsUndecoded(output)
```

Listing 8: Precopscan Discovery Engine (pseudocode)

20.4 G.4 Vault Health State Machine (TypeScript Replica of brc20_-cdp.simf)

The following vault lifecycle is reconstructed by Precopscan identically to the Simplicity Bit Machine adjudication:

Event Detected	Vault Status	Trigger Condition
MINT op in OP_RETURN + P2TR output	*Open / Healthy*	$CR \geq 150\%$
CDP state blob found in witness	*Updated*	New collateral / price
$120\% \leq CR < 150\%$	*At Risk*	Oracle price update
$CR < 120\%$	*Liquidatable*	Covenant allows seizure
BURN op in OP_RETURN + dual-input tx	*Closed / Repaid*	BTC released
BURN op + liquidation gage input	*Liquidated*	Treasury receives penalty

Table G.1: Precopscan CDP Vault Lifecycle State Machine

20.5 G.5 Architectural Significance

Precopscan demonstrates a fundamental property of the PRECOP sovereignty model: **the protocol state is fully recoverable from Bitcoin L1 alone**. No sidechain, no Layer 2, no oracle API endpoint is required to reconstruct the current state of every vault, every DEX position, and every token balance. The seven probe addresses are the only external dependency — and their necessity is itself a consequence of the cryptographic commitments enforced by the TapLeaf covenant. The observer and the protocol are thus logically inseparable: one cannot exist without implying the other.

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